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AN EXPERIMENTAL STUDY OF

PRESSURE WAVES IN GUN CHAMBERS

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U. S. NAVAL PROVING GROUND
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U. S. Naval Proving Ground
Dahlgren, Virginia

An Experimental Study of

Pressure Waves in Gun Chambers

by

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and
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Weapons Development and Evaluation Laboratory

NPG REPORT NO. 1534

Task Assignment No.
NPG-S6-2d-2-1-56
and
Foundational Research
Project NPG-W-1802-4

25 April 1957

APPROVED: G. H. WALES
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Ordnance Officer
By direction

CONTENTS

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ABSTRACT

Experimental studies of the space-time variations in
pressure in gun chambers leads to the conclusions that
pressure waves are manifestations of standing pressure
waves in the propellant gases and that these waves dev-
elop as a result of pressure gradients set up in the
chamber in the initial stages of the pressure cycle in
combination with motion and differential packing of the
propellant produced by the gradients.

FOREWORD

The phase of the study concerned with the nature of pressure waves was carried out under Task Assignment NPG-S6-2d-2-1-56, "Gun Propellant Ignition Studies", authorized by reference (a). This phase of the study is treated here in essentially the form in which it was originally presented at the Seventh AXP Tripartite Conference (reference (b)) and again later in the preprints of the Second Symposium on Solid Propellant Ignition (reference (c)). The second phase of the study, dealing with the origin of pressure waves, was carried out under Foundational Research Project NPG-W-1802-4, "Pressure Waves in Propellant Gases", authorized by reference (d)). This phase of the study was presented in outline at the Second Symposium on Solid Propellant Ignition (reference (c)) and is presented here in expanded form.

This report was reviewed by the following personnel of the Weapons Development and Evaluation Laboratory.

R. I. ROSSBACHER, Head, Initial Ballistics Branch
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INTRODUCTION

In the literature pertaining to pressure waves in gun chambers, these waves are almost invariably attributed to "sporadic burning" of the propellant, with the implication that an erratic and uncontrolled mode of burning is involved in the formation of pressure waves. This conception leads, understandably, to the attitude that the presence of pressure waves indicates a potentially dangerous condition; that any chance round may develop a dangerously high pressure in the gun chamber. A second attitude, that muzzle velocity is more variable from rounds producing pressure waves than from similar rounds producing smooth pressure curves, seems also to result from the "sporadic burning" concept of pressure waves. The studies conducted at the Naval Proving Ground on the nature and origin of pressure waves does not support the "sporadic burning" theory of pressure waves, removes much of the cause for considering these waves as potentially dangerous, and indicates that pressure waves are not to be considered prime sources of velocity variation.

The study of pressure waves in gun chambers which has been carried out at the Naval Proving Ground divides into two phases. The first phase was concerned primarily with establishing the nature of these waves and led to the formulation of the standing wave hypothesis of pressure waves. The second phase, which grew out of the first as a logical continuation of the study, has been concerned with the manner in which pressure waves originate and develop in gun chambers. Though it is not considered that this latter phase has been studied exhaustively, the work to date has led to an identification of the more important parameters involved in the origin and development of pressure waves, has shown the manner in which two of these parameters may interact in forming waves, and has permitted the formation of a working hypothesis of the mechanisms by which pressure waves originate in gun chambers. The two phases of the study will be treated in the order in which they were chronologically pursued.

THE NATURE OF PRESSURE WAVES

The nature of pressure waves was deduced from a study of the space-time variations in pressure in several gun chambers. Pressure-time curves obtained simultaneously at two to five positions in the gun chambers constituted the basic data. Data of this type were accessible from two conventional naval guns, one hypervelocity experimental gun, and a gun-simulator commonly referred to as a "blow-out" gun. Pressure curves exhibiting well-defined pressure waves were available for study from each of these guns. In all of the examples studied, it was found that the space-time relations of the pressure waves could be interpreted on the hypothesis of a standing pressure wave in the propellant gases. Typical samples of the experimental evidence forming the basis for this hypothesis follow.

We will consider first a typical set of pressure records from the blow-out gun in which the standing wave character of the pressure waves is somewhat more explicitly demonstrated, because the chamber of this device remains fixed in length during the entire pressure cycle.

The blow-out gun was manufactured at the Naval Proving Ground as an experimental device for studying the ignition and early burning of propellants. A 5"/38 caliber gun barrel was cut off approximately 9.5 inches forward of the origin of the bore and modified in such a way that an orifice could be installed at the position corresponding to the base of a seated projectile in the normal gun. Three pressure gauges were installed in the chamber wall to measure chamber pressures. One gauge was located at the center of the chamber, one three inches forward of the breech face, and the third three inches aft of the orifice. Any type of charge which can be made up in a standard 5"/38 case can be fired in this device. With the proper choice of orifice diameter, the pressure histories recorded at the three gauge stations in the blow-out gun are similar in space and time relations to those obtained in the conventional gun firing a like charge. The advantages of the blow-out gun are that the maximum pressures are only about half those obtained in a conventional gun and that no projectile is required. The general similarity of the pressure histories recorded in the blow-out

gun to those of a standard gun will be seen in comparing
Figures 1 and 2. By duplicating the chamber length of a
5"/54 caliber gun (by moving the orifice forward six inches)
the blow-out gun reproduces equally well the pressure histories
obtained in the 5"/54 gun.

A set of blow-out gun pressure records with pronounced
pressure waves is presented in Figure 1. This set was
obtained in the firing of a standard 5"/38 service charge
ignited with a primer venting in the forward section of the
charge. Descriptively, we have here pronounced waves on
the records from the two ends of the chamber with the com-
pressions and rarefactions 180° out of phase at the two
ends. But no comparable waves are present on the record
from the center of the chamber. In Figure 1A we have
plotted only the wave components of the pressure curves
shown in the first figure. These curves were obtained by
taking the difference between the three pressure records
and a smooth curve drawn through the points of equal pres-
sure on the three pressure curves. This wave pattern
immediately suggests a standing wave mode of vibration.
Further consideration shows that a standing wave in a tube
closed at both ends vibrating at the fundamental frequency
of the tube would give this wave pattern and would also be
consistent with further deductions we can make.

Since there is a sudden reduction in diameter of the
blow-out gun chamber at the orifice, a wave in the chamber
would be partly reflected without change in sign at the
orifice. In the firing considered here, the orifice
effected a 56% area closure of the chamber. Therefore the
orifice should function in part as a closed end. The
damping of the wave can be attributed, at least in part,
to the fact that there is only partial reflection of the
wave at the orifice.

Several considerations make it probable that the
vibration is at the fundamental frequency of the chamber.
In the early part of the pressure cycle, the velocity of
the wave in the chamber can be expected to be close to
that of the velocity of sound in air. If we calculate
the wave velocity assuming a wave length twice that of the
chamber (the fundamental wave length) and determine the
period of the wave for the first quarter-cycle of the first
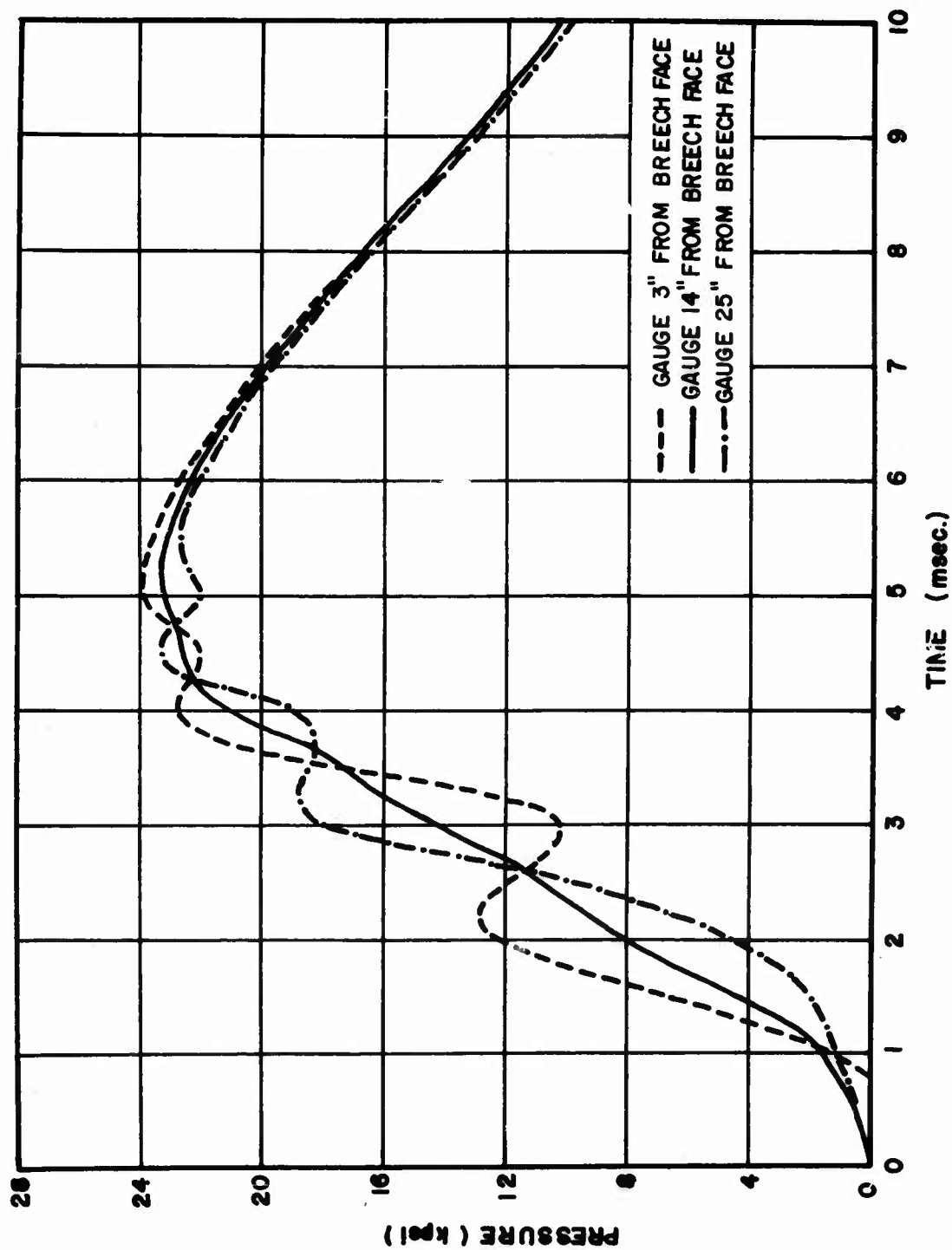pressure oscillation on the pressure records, we obtain a
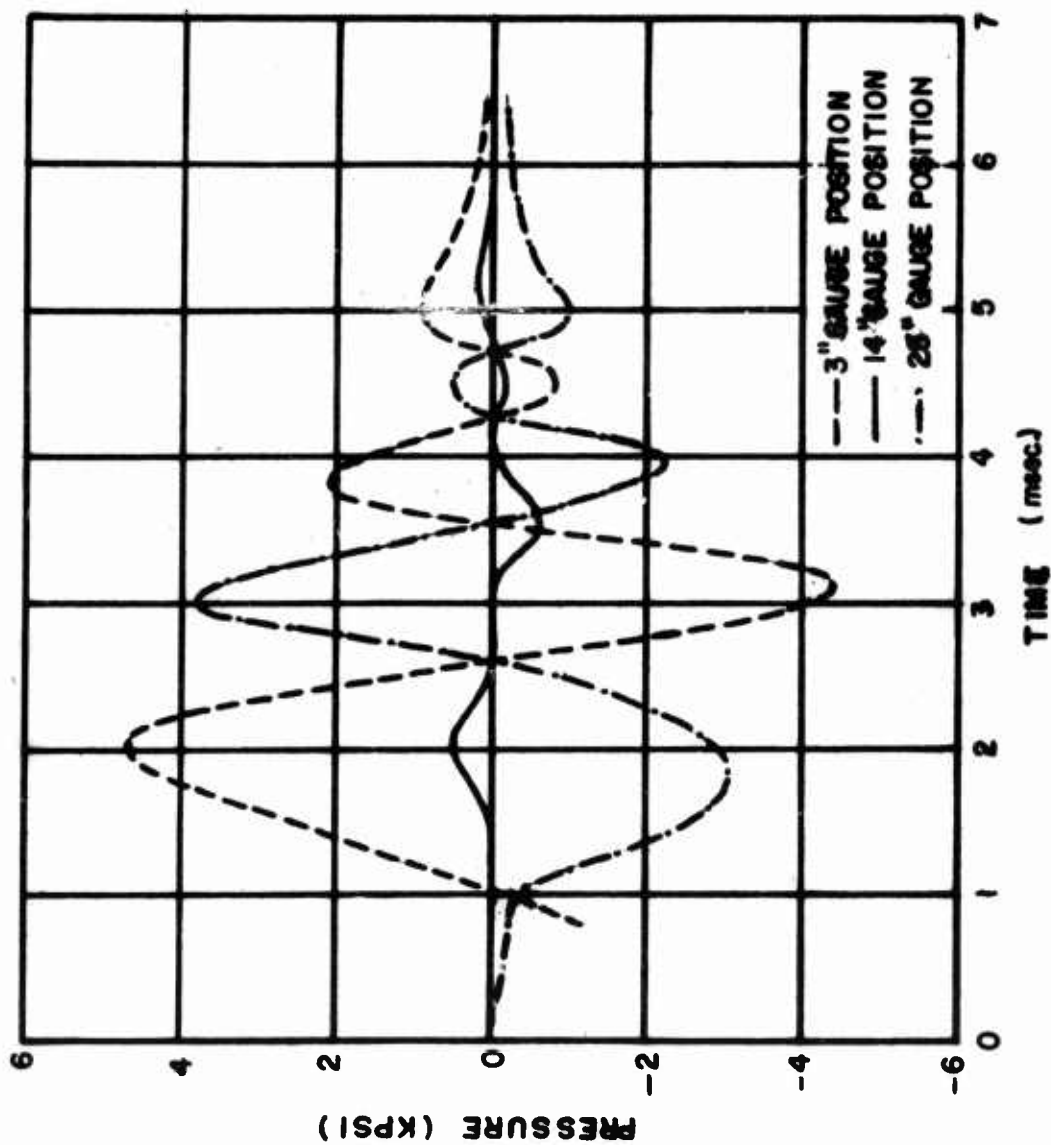
FIGURE 1. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE IA PRESSURE WAVES IN 5"738 BLOWOUT GUN

Legend:
--- 3" GAUGE POSITION
—— 14" GAUGE POSITION
–·– 28" GAUGE POSITION

velocity of about 1200 ft/sec. Using the period for the
first half cycle instead, we obtain 1550 ft/sec for the
velocity. We of course expect the propagation velocity to
increase as the pressure rises as a result of the changes
taking place in the medium. If the vibrations represented
a harmonic instead of the fundamental, the computed veloc-
ities would come out one-half, one-third, etc. of the above
values, depending on the harmonic selected.

     We can also rule out all even harmonics since any of
these would produce compressions and rarefactions simul-
taneously at both ends of the chamber and the opposite con-
ditions (rarefactions and compressions) at the center of
the chamber. Pressure records at stations midway between
the center gauge and end gauges show waves with amplitudes
somewhat less than those recorded at the ends of the chamber,
and in phase with the vibrations at the ends. The third
harmonic would produce wave action at these intermediate
gauge stations approximately 90° out of phase with that at
the end gauges and at approximately twice the amplitude.
The fifth harmonic would produce antinodes at approximately
the positions of all five gauge stations.

     Let us now consider a set of pressure curves from a
conventional 5"/38 gun. A typical set of records from this
gun is shown in Figure 2. The powder, charge weight, and
igniter were the same as those used to obtain the blow-out
gun records considered above, and the pressures were
recorded at approximately the same positions in the chamber
(3, 15 and 23 inches from the breech face as compared to
3, 14 and 25 inches in the blow-out gun). The general
similarity of the wave pattern exhibited by this set of
records to that of the set from the blow-out gun in Figure 1,
particularly in the early stages, is at once evident.

     In Figure 2A we have plotted only the wave components
of the pressure curves shown in the previous figure. These
curves show the differences between the three pressure
records and a smooth curve drawn through the points of
equal pressure on the three pressure curves.

     In Figure 3 we have shown the relative wave amplitudes
from the previous figure on a space-time plot. The pro-
jectile travel curve included on the plot was obtained by
integrating twice a projectile acceleration curve computed
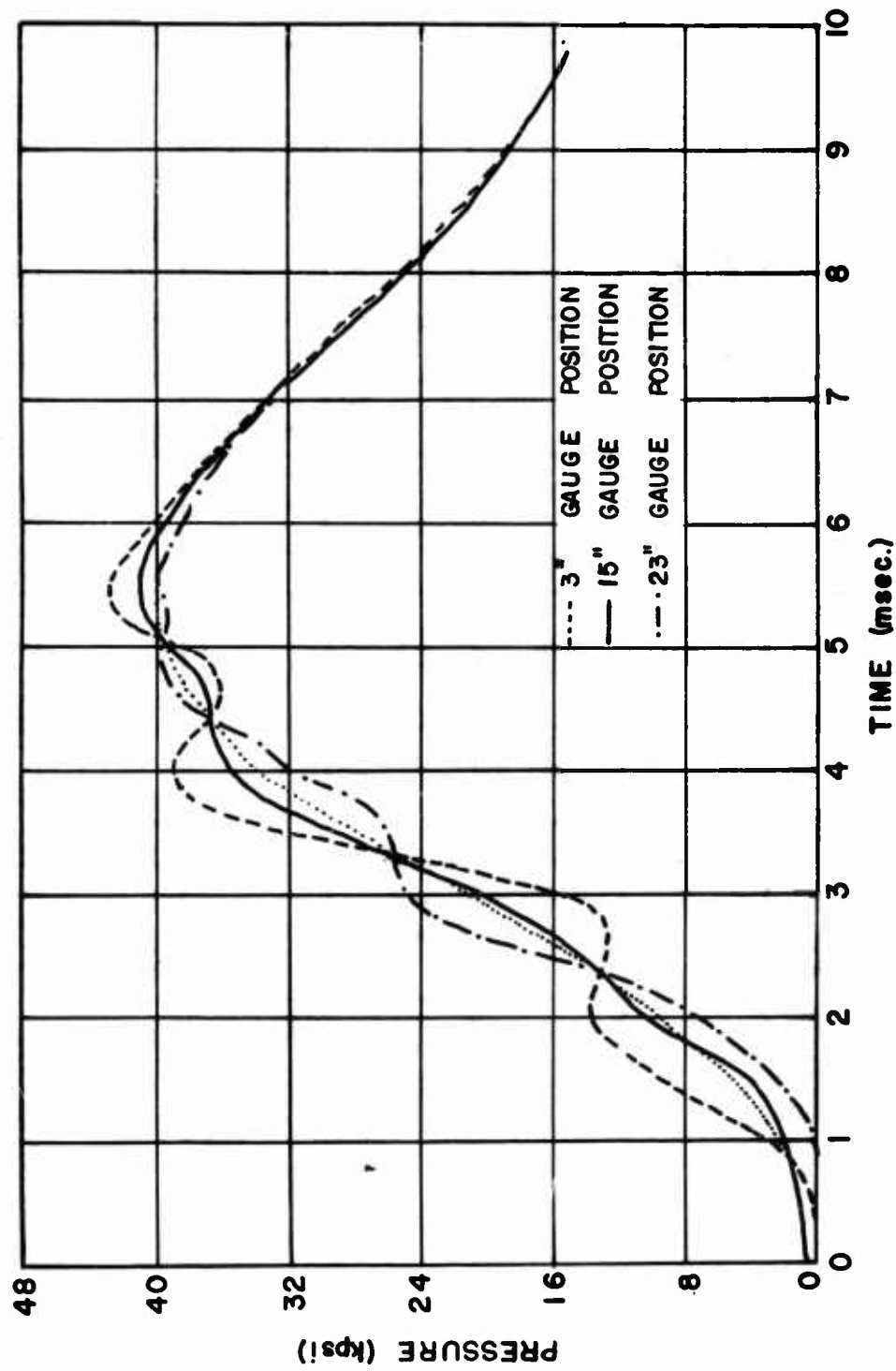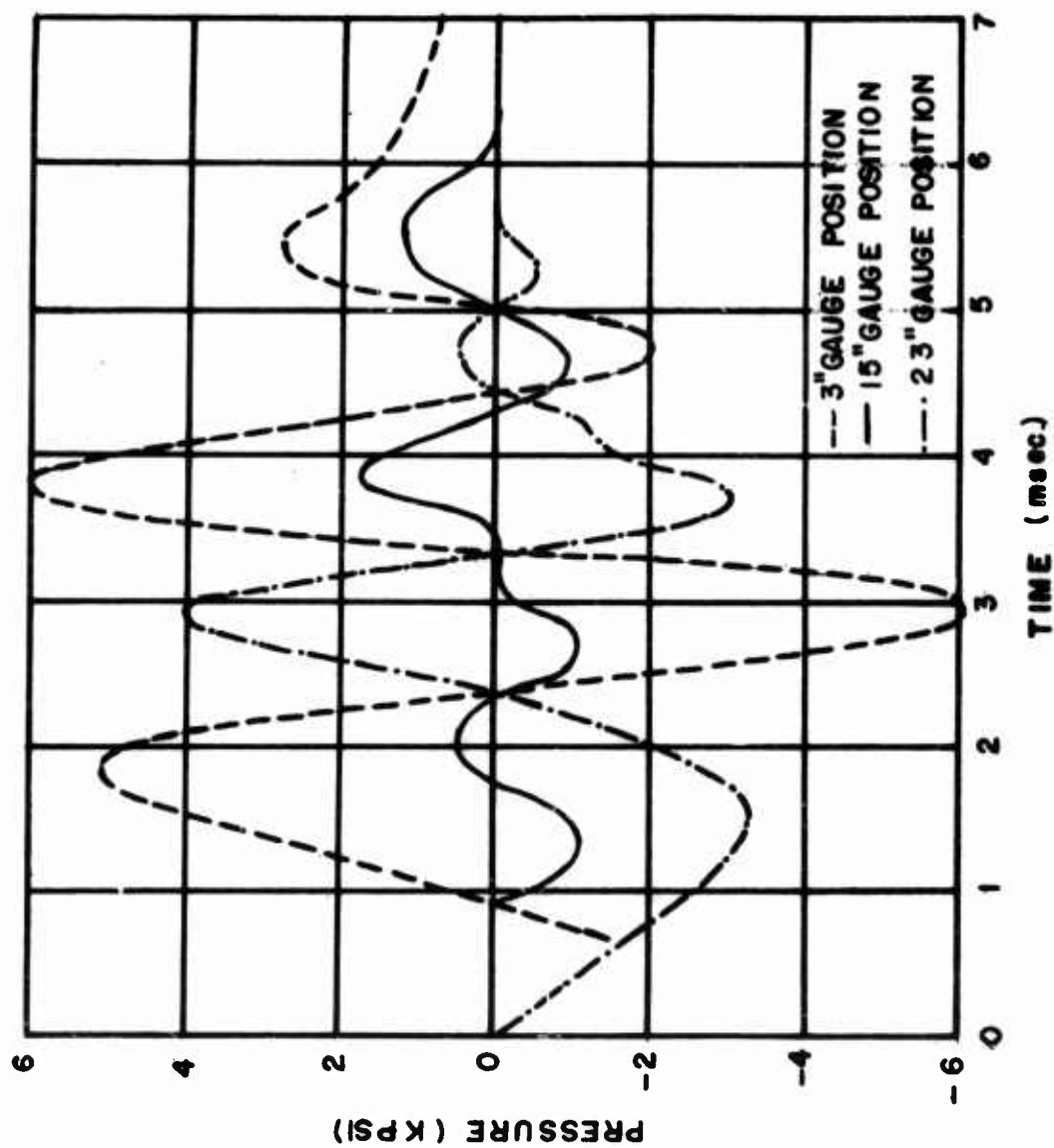
FIGURE 2. PRESSURE-TIME CURVES FROM 5"/38 GUN
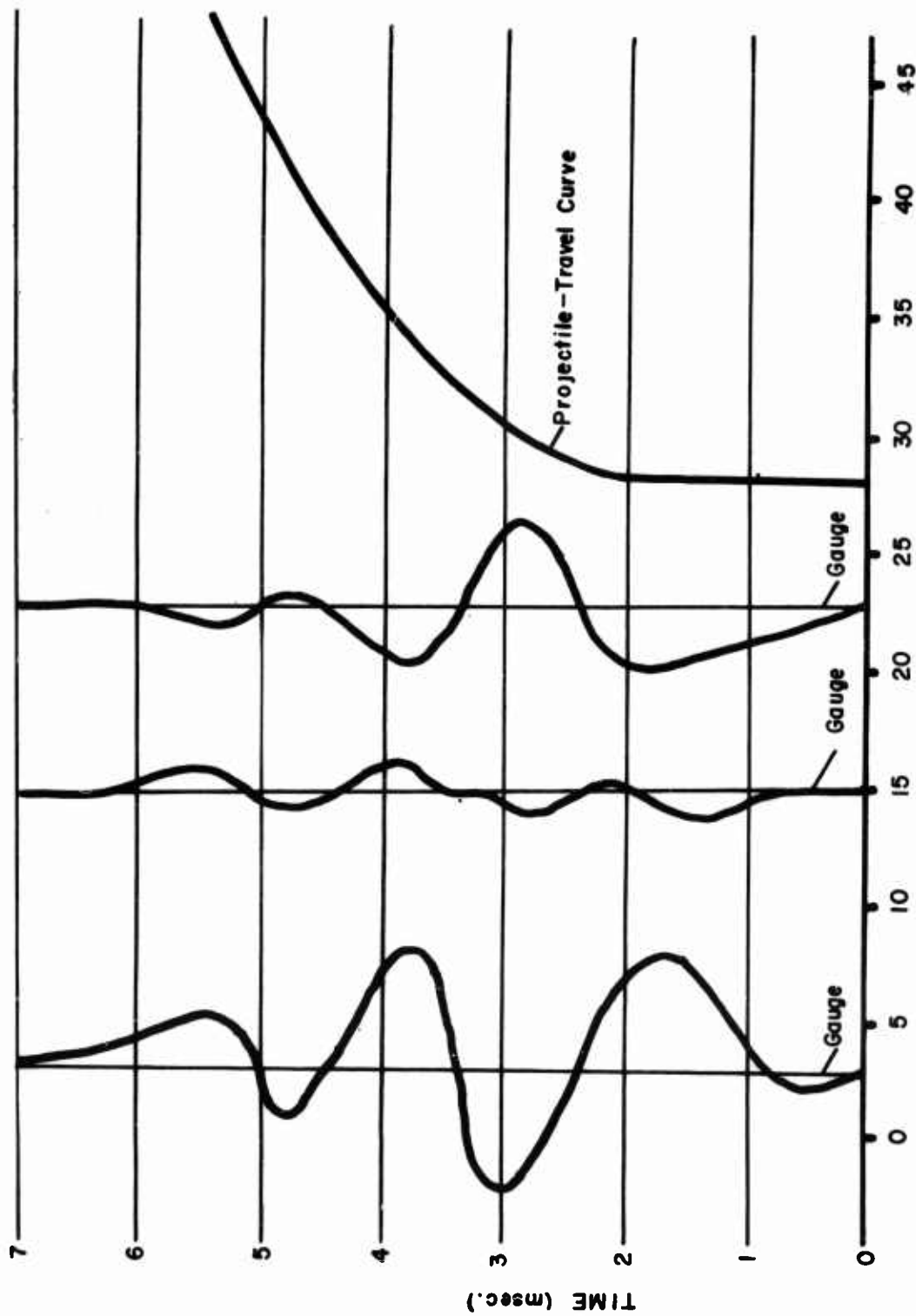
FIGURE 2A. PRESSURE WAVES IN 5"/38 GUN

DISTANCE from BREECH FACE (in.)

FIGURE 3. PRESSURE WAVES IN 5"/38 GUN

Compressions are to right and Rarefactions to left of vertical lines

from the average chamber pressure. While this travel curve
is only an approximation, it is in close agreement at
maximum pressure with the projectile motion computed by the
Hunt-Hinds System, and is sufficiently realistic for our
present purposes.

These waves also can be interpreted as the result of
a standing wave mode of vibration in the gun chamber if the
increase in chamber length accompanying the forward motion
of the projectile is taken into account. In Figure 3 it
will be observed that as the propellant gas column
increases in length, oscillations appearing on the center
gauge become in phase with those on the rear gauge, but that
the amplitudes of these oscillations are less than those at
the rear gauge position.* On the other hand, the oscil-
lations at the forward gauge decrease in amplitude during
this time and practically disappear at the time this gauge
becomes about half way between the base of the case and the
base of the projectile. All of these observations are in
accord with the results to be expected from a standing wave
in a tube increasing in length with time. It appears in
this case that only a vibration at the fundamental fre-
quency of the chamber can give us the wave pattern we
observe on the center and forward gauges as these are, in
effect, moved rearward as the propellant column expands in
length. The condition here is analogous to that of a
standing wave on a spring which is fixed at one end, but is
being extended at the other end. That the wave motion is
able to expand into the total space behind the projectile
appears plausible in view of the fact that in this gun
there is practically no change in diameter between the
chamber and the bore of the gun. As will be noted later,
this extension of the standing wave does not appear to
occur in a gun with pronounced chambrage.

*We cannot account for the small oscillations occurring
on the center gauge record in the early part of the pres-
sure cycle. They may possibly represent only an oscil-
lation of the antinode position. There is a definite
change in frequency and phase at the time considered
above, however.

We have also studied the space-time relations of the waves observed on pressure-time records from 5"/54 blow-out gun and 5"/54 gun firings. The data from these two guns were in agreement in all essential aspects with the interpretations made of the 5"/38 data. To consider it further here would only lead to a repetition of what we have already stated above. We may point out, however, that the 5"/54 gun is similar to the 5"/38 in that it does not have a pronounced chambrage.

Let us next consider the pressure waves observed on a 4"/3" gun firing. This gun was designed as a hypervelocity squeeze-bore gun, but the firings considered here were made without the 3" bore section attached to the 4" barrel. A typical set of pressure records obtained from the chamber and several positions along the bore is presented in Figure 4. Applying the same general method of analysis to this set as was used on the 5"/38 gun records, we obtained the wave patterns shown in Figure 5. We have included the waves from only the first three bore positions here. The projectile travel curve in this case was determined from the pressure records along the barrel.

The wave pattern we have here appears to be that of a standing wave in the chamber, but of a traveling wave in the bore of the gun. If we consider the chamber geometry of this gun, we see that a wave action of this nature is plausible with this geometry. This gun has pronounced chambrage, there being a decrease from a diameter of seven inches to four inches at the forward end of the case (see Figure 5). A wave originating in the chamber would, upon reaching the necked-down section, be partly reflected and partly transmitted. A standing wave mode of vibration could then be set up in the chamber by the reflected part of the wave while the transmitted part would travel down the bore as a progressive wave. The restriction in the case here appears to operate in a manner similar to the orifice in the blow-out gun and as wave theory indicates it would.

While we have presented here only one set of pressure records from each gun system under study, these sets are typical in as much as they are reproducible on repeated firings.

Thus, in the five gun systems we have considered, the space-time relations of the pressure waves, as revealed by simultaneous pressure-records at several positions in the
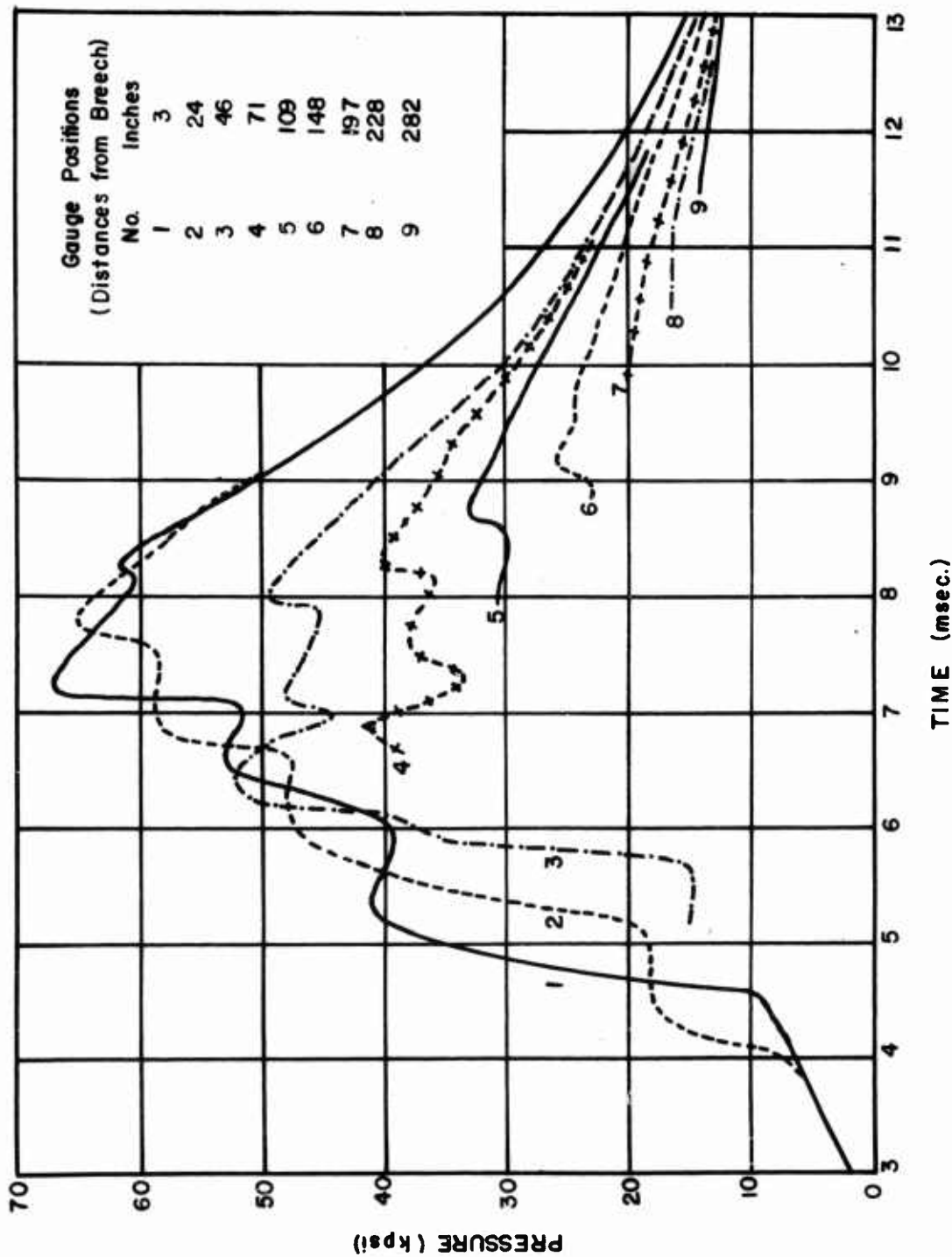
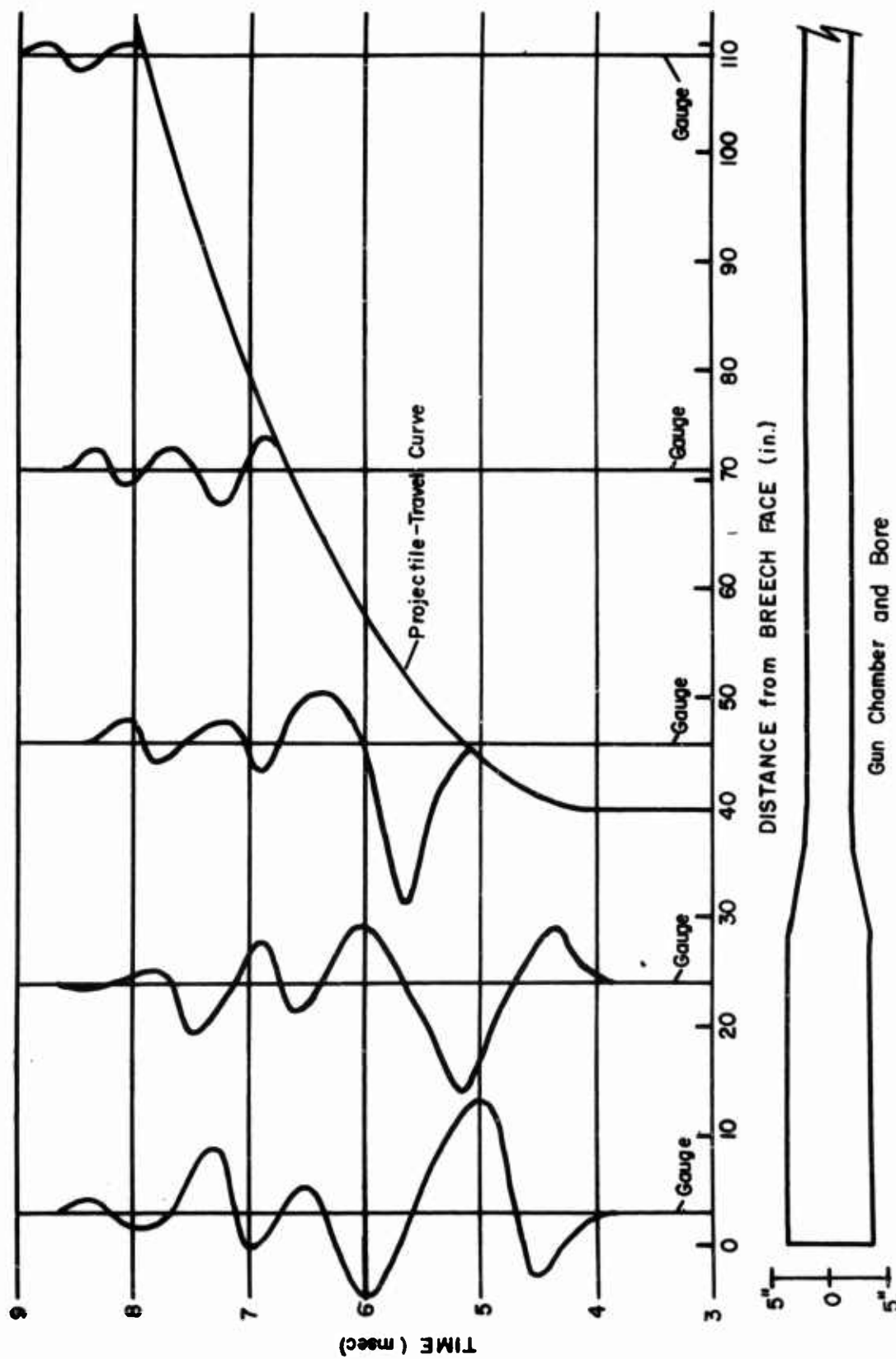FIGURE 4.   PRESSURE–TIME CURVES FROM 4"/3" EXPERIMENTAL GUN

FIGURE 5. PRESSURE WAVES IN 4"/3" EXPERIMENTAL GUN

Compressions are to right and Rarefactions to left of vertical lines

gun chambers, support the conclusion that these waves are manifestations of standing pressure waves in the propellant gases.

This interpretation of pressure waves implies that "roughness" of propellant burning is a space-dependent variable and has practical applications for the propellant evaluator. If we are interested in the degree of "roughness" of the pressure curve, we should locate our pressure gauge near the breech end of the gun chamber because the manifestations of "roughness" will be most pronounced in this region. On the other hand, if we are more interested in mean chamber pressures, we would do well to locate our gauge near the center of the chamber and thereby obtain pressure curves relatively free of oscillations. Gauges located near the base of the seated projectile would give data pertinent to shot-start pressure and early projectile motion.

THE ORIGIN AND DEVELOPMENT OF PRESSURE WAVES

While the standing wave hypothesis of pressure waves describes the nature of these waves, it does not explain the manner in which they originate and develop in gun chambers. A theory of the mechanisms by which standing pressure waves originate in gun chambers is a prerequisite, first, to an evaluation of the ballistic significance of these waves, and second, to the control of these waves in practical ballistic applications.

Since pressure waves are, fundamentally, oscillatory pressure gradients, these waves must arise from pressure gradients set up in the gun chamber which, under proper conditions, become oscillatory and develop into standing waves. The problem of the origin of pressure waves thus resolves into one of identifying the sources of these initial pressure gradients and of explaining the manner in which they develop into standing pressure waves. A considerable volume of pressure-time data from a wide variety of test firings carried out at the Naval Proving Ground was reviewed from this point of view. While these data suggested a number of parameters which might contribute to initial pressure gradients in the gun chamber, the parameters which appeared to be most pertinent for further study were (1) the axial position within the charge at which the propellant was first ignited, and (2) the ullage or free space above charges which did not fill the available

chamber volume. In connection with both of these para-
meters, it was observed that the rate of pressure rise
increased with increasing distance through the chamber from
both the point of ignition and the ullage. These differ-
ential rates of pressure rise through the chamber thus
appeared to be sources of pressure gradients which might
develop into standing pressure waves in the gun chamber.

The effect of point of ignition on the pressure history
is illustrated by the pressure-time curves in Figure 6. We
have shown here three pressure-time curves recorded at the
breech end of the chamber in the firing of three rounds in
a 3"/70 caliber gun. One round was ignited by approximately
point source ignition near the rear of the chamber, the
second was ignited near the center of the chamber, and the
third near the forward end of the chamber. The rounds were
otherwise identical and the propellant completely filled the
case. We note, first, that the two end-ignited rounds pro-
duced pronounced pressure waves, while wave action is com-
pletely absent in the center-ignited round. Second, we note
that the wave patterns from the two end-ignited rounds are
180° out of phase. Reversing the point of ignition also
reverses the phase of the wave. The wave pattern formed by
these two pressure records is identical to that to be
expected from the two ends of the chamber from a single
round ignited at one end of the chamber.

An effect of the configuration of the ullage on the
pressure history is illustrated by the pressure-time curves
of Figures 7 and 8. In Figure 7, the pressure curve with
the pronounced pressure wave was recorded at the breech end
of a 3"/50 caliber gun during the firing of a service
charge of a slotted-tube propellant. There was a rather
large ullage, equal to about one-third the total case
volume, at the forward end of the case in this round. When
this equivalent ullage volume was distributed longitudi-
nally along one side of the case (and thereby producing a
uniform axial distribution of the powder in the case) the
smooth curve of Figure 7 was obtained. This uniform axial
distribution of the powder was maintained during handling
of the round by inserting a foam plastic rod of the proper
dimensions along the periphery of the case before pouring
the powder. Mk 42 primers were used in both rounds.
Hollow pyralin cylinders were as effective as the foam
plastic rods in eliminating the pressure waves. Similar
results were obtained with a deterrent-coated powder. Two
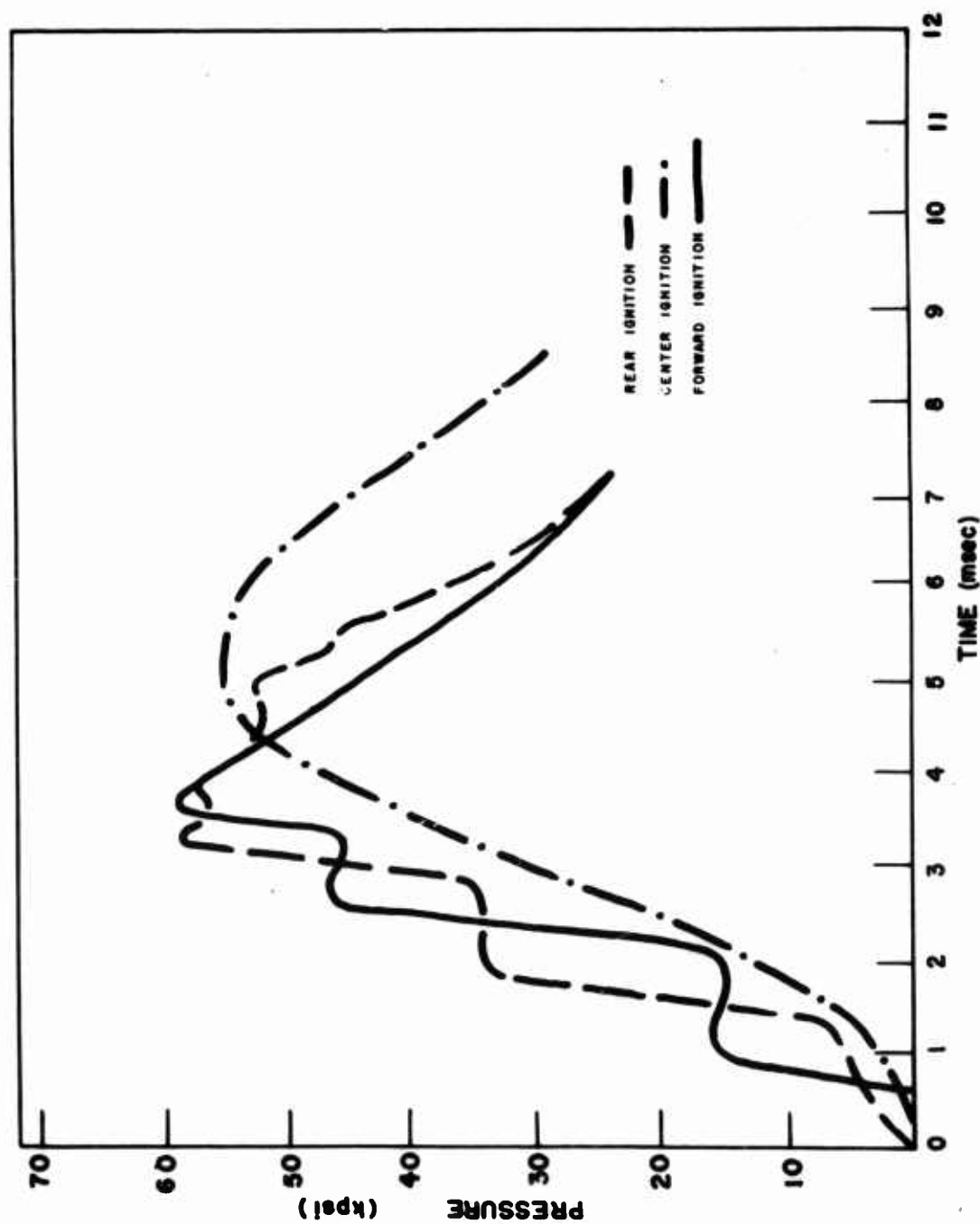pressure curves from the firing of this powder in a

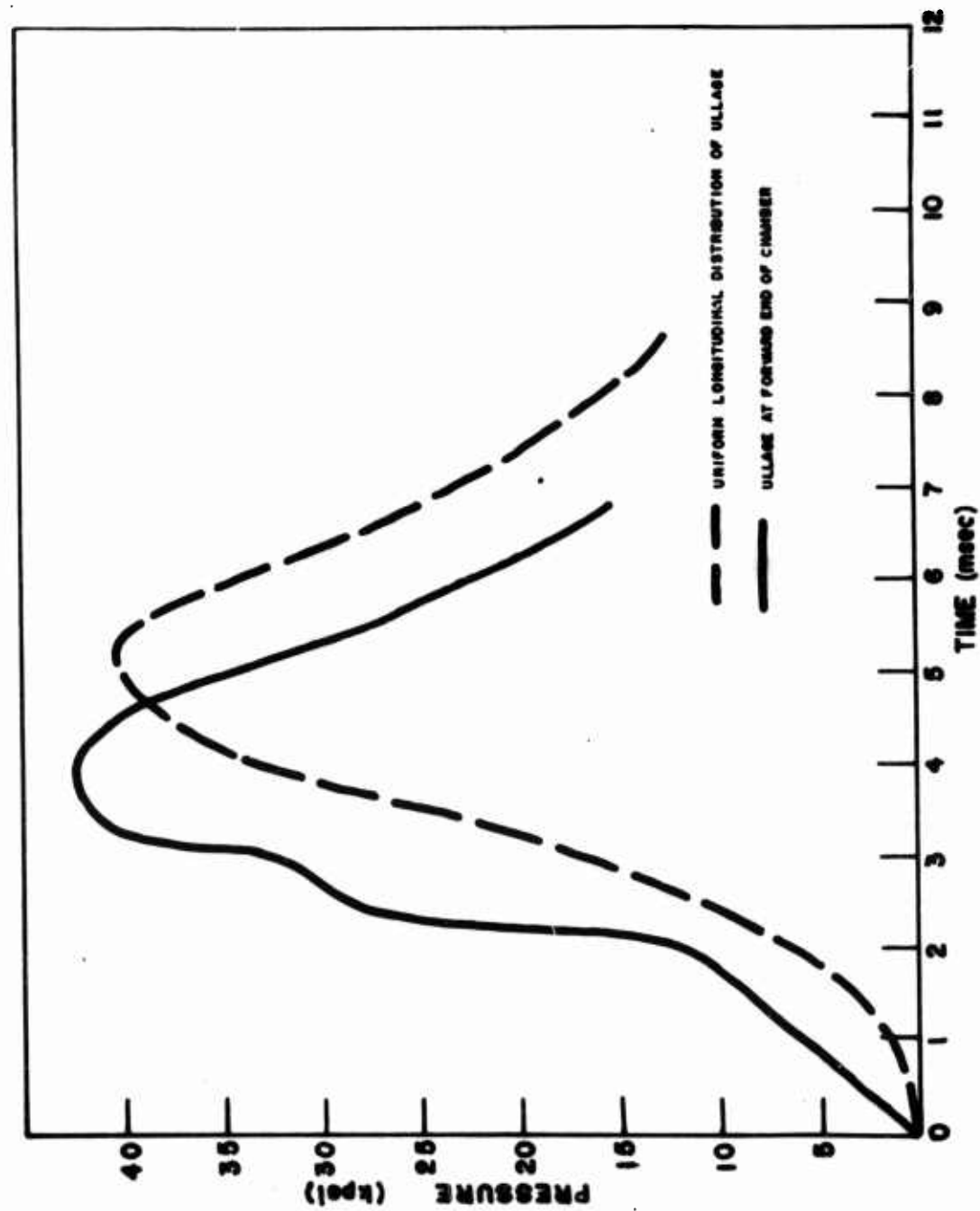FIGURE 6. EFFECT OF POINT OF IGNITION UPON PRESSURE HISTORY

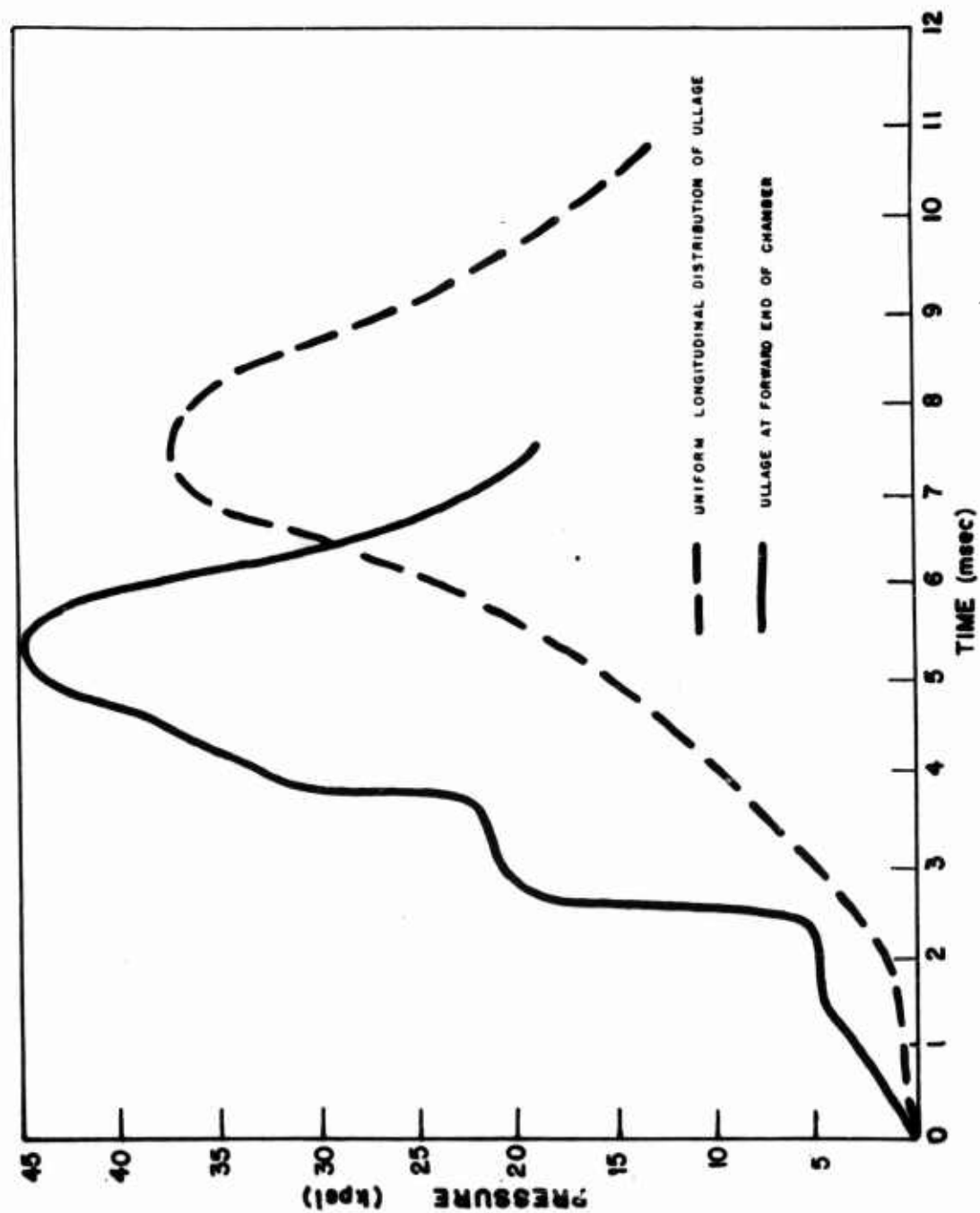FIGURE 7. EFFECT OF CONFIGURATION OF THE ULLAGE ON THE PRESSURE HISTORY

FIGURE 8. EFFECT OF CONFIGURATION OF THE ULLAGE ON THE PRESSURE HISTORY

3"/50 caliber gun are presented in Figure 8. This powder also produced pronounced pressure waves when poured in the conventional manner with a large void at the forward end of the case, but smooth pressure curves were obtained when the ullage was distributed longitudinally along one side of the case.

Having accumulated considerable evidence, similar in nature to the two preceding examples, that both the axial point at which the charge was ignited and the location and extent of the ullage were significant parameters in the origin and development of pressure waves, we next considered the possible interaction of these two factors in the formation of waves. It seemed reasonable to expect that the contribution of the ullage toward wave formation would tend to reinforce or neutralize the contribution of the ignition, depending on their relative spacial relations in the chamber. Combining this assumption with the fact that the initial rate of pressure rise could be expected to increase through the chamber both with increasing distance from the point of ignition and with the position of the ullage, a theoretical prediction of the space-time variations in pressure with varying spatial relations of the ignition and the ullage appeared feasible. However, the relative effectiveness of either ignition or ullage in determining the phase relations and amplitudes of the wave action which might develop in the chamber would be expected to vary with different chamber-igniter-propellant combinations.

This working hypothesis of the interaction of the point of ignition and location of the ullage in the formation of pressure waves predicts these general results: The largest amplitude pressure waves would result from rounds with the point of ignition adjacent to the ullage. The phase of the wave would be reversed by locating the point of ignition and ullage at the opposite end of the gun chamber. The wave amplitude would decrease as the point of ignition was moved away from the ullage toward the opposite end of the chamber with the lowest relative amplitude obtained with ignition and ullage at opposite ends of the chamber. Two ullages, one at either end of the chamber would neutralize each other, and the resulting wave would be the result primarily of the axial location of the point of ignition. Pressure waves would not develop in rounds with split ullages and with point of ignition at the center of the chamber.

By assigning relative effectivenesses in initiating
wave action to the two parameters, we found we could, in
most cases, predict, in a qualitative sense, the phase
relations and amplitudes of the space-time variations in
pressure for a given spatial relation of point of ignition
and ullage. However, though agreement with empirical
results were good, in many cases the empirical results were
from firings in which possible contributions from other
parameters could not be eliminated.

To test the validity of our working hypothesis of the
interaction of point of ignition and position of the ullage
in the formation of pressure waves under controlled con-
ditions, we carried out a firing program in the 5"/38 blow-
out gun. This program consisted of a block of nine rounds
which comprised all combinations of rear, center and forward
ignition with rear, forward and split ullages. The primers
used in these firings were designed especially for these
tests in an attempt to obtain, insofar as practical, a uni-
form type of ignition at the different positions in the
charge. The booster charge (300 grains of black cannon
powder) was loaded in the vented section of standard primer
tubes and maintained in this position, by spacers forward
and aft of the vented section, until ignited. The vented
section comprised 12 holes arranged in four rows, with the
holes spaced one inch apart in the rows and the holes
staggered in adjacent rows. This arrangement of the holes
restricted the vented section to about 2.5 inches in the
axial direction. The volumes within the primer tubes
available to the primer gases were the same for each group
of three primers used with each ullage arrangement, but
differed slightly for the three different ullage con-
figurations.

The sets of pressure-time curves obtained in the firing
of the nine test rounds are presented in Figures 9
through 17. In addition to the pressure curves obtained at
3, 14 and 25 inches in the blow-out gun chamber, a sche-
matic diagram is included in each figure which shows the
spatial relations of the propellant, igniter, ullage, pres-
sure gauges and orifice in the chamber.

Approximations to the pressure-space relations existing
in the chamber during the first 5 to 6 milliseconds of the
pressure cycle for the nine rounds are presented in
Figures 9A through 17A. These curves are the results of

FIGURE 9. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE 9A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE 10. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE 10A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE 11. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE IIA

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE 12. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE 12A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE 13. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE 13A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

FIGURE 14. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN
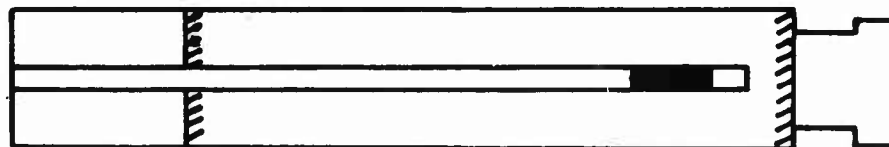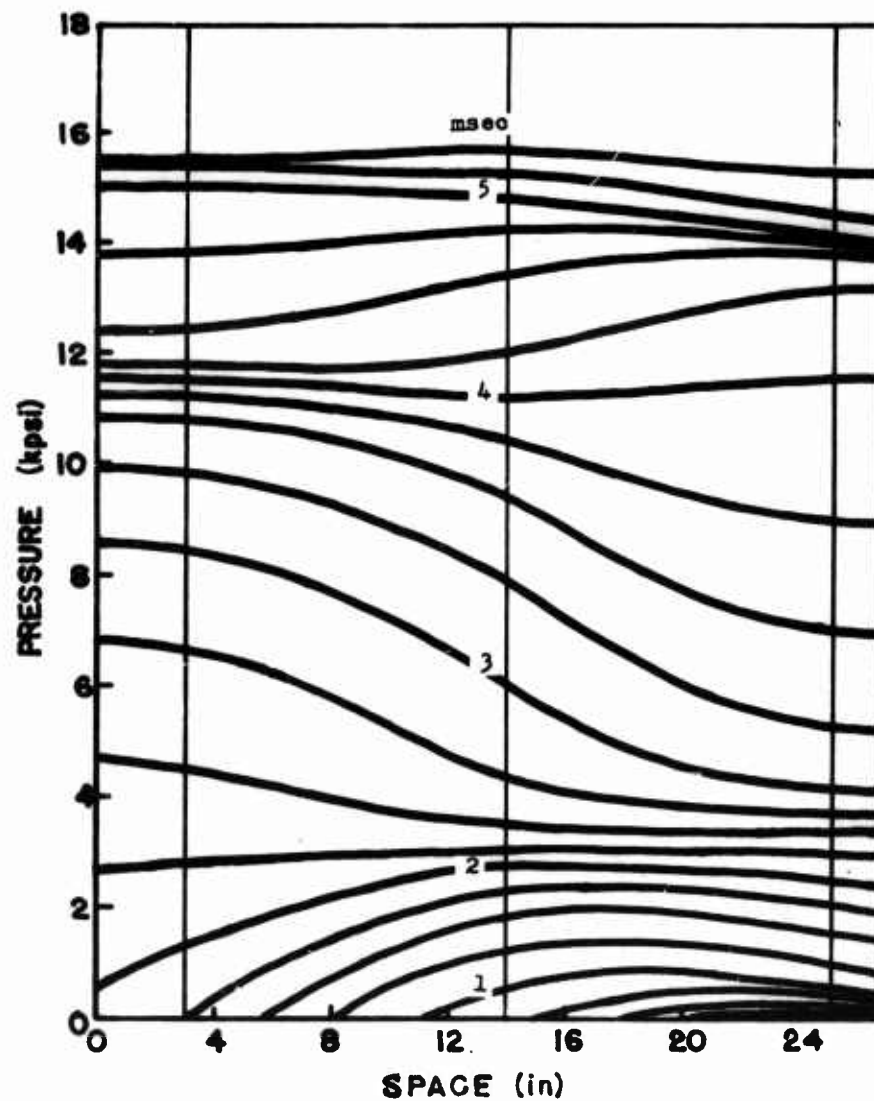
FIGURE 14A
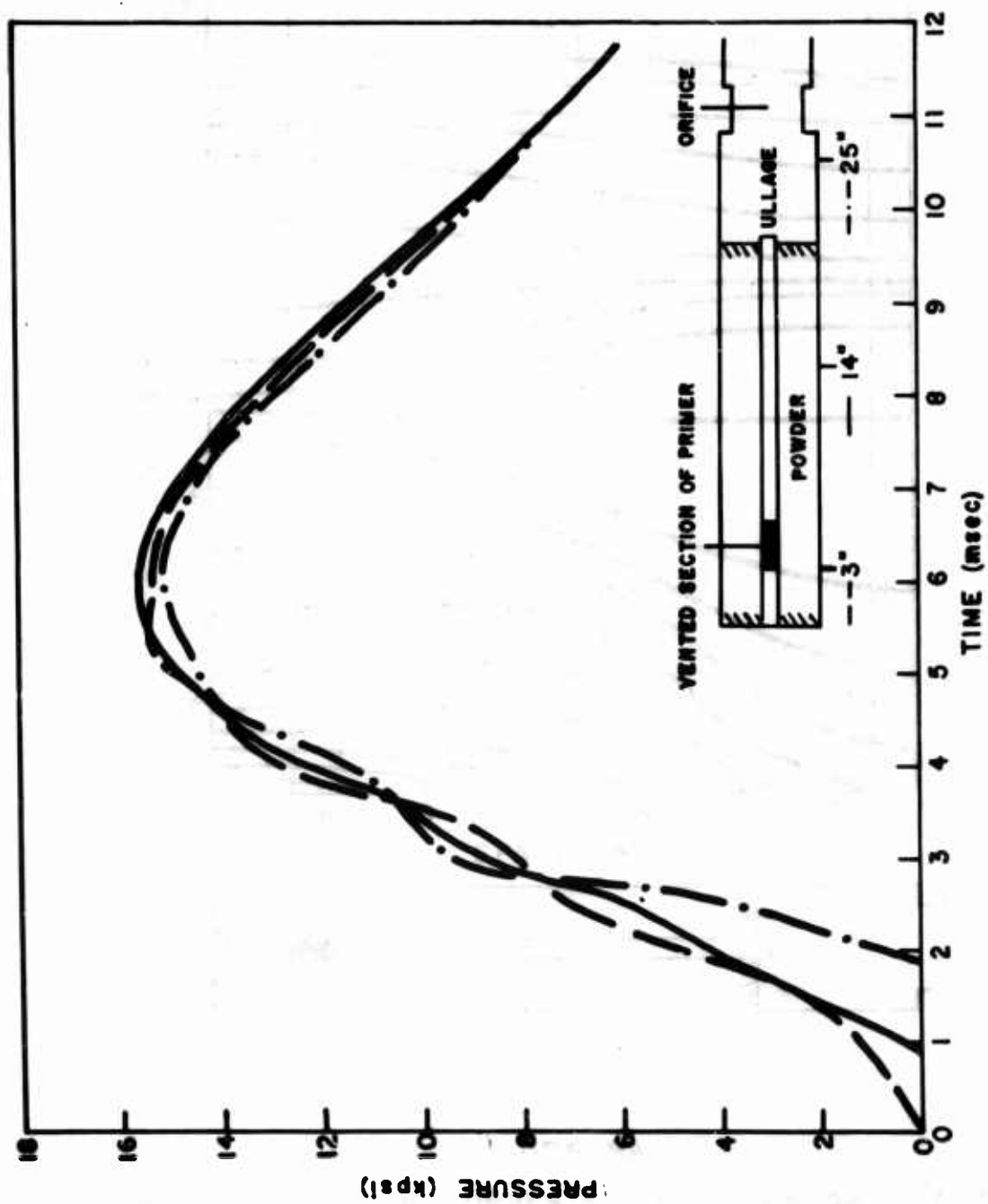
PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN
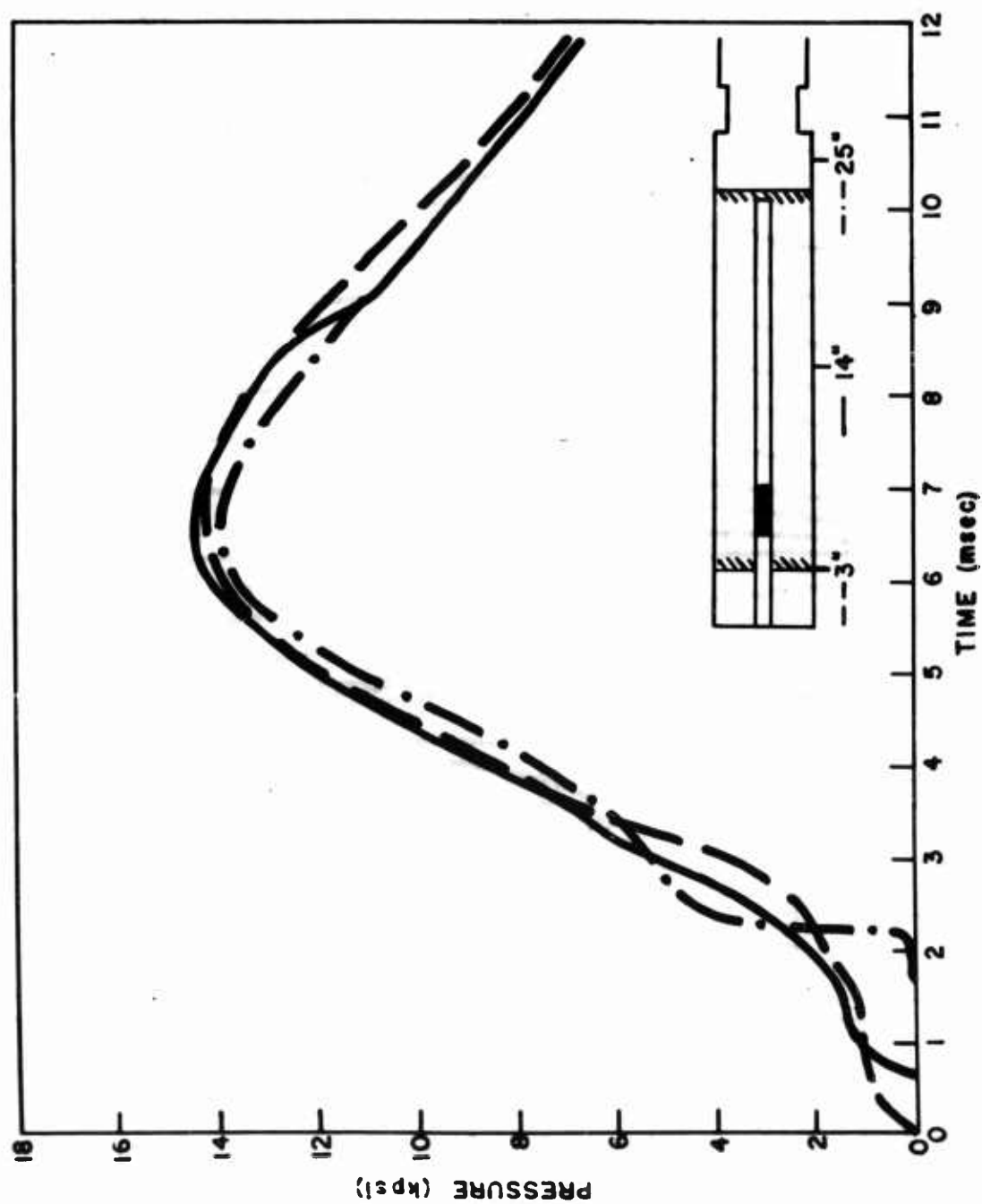
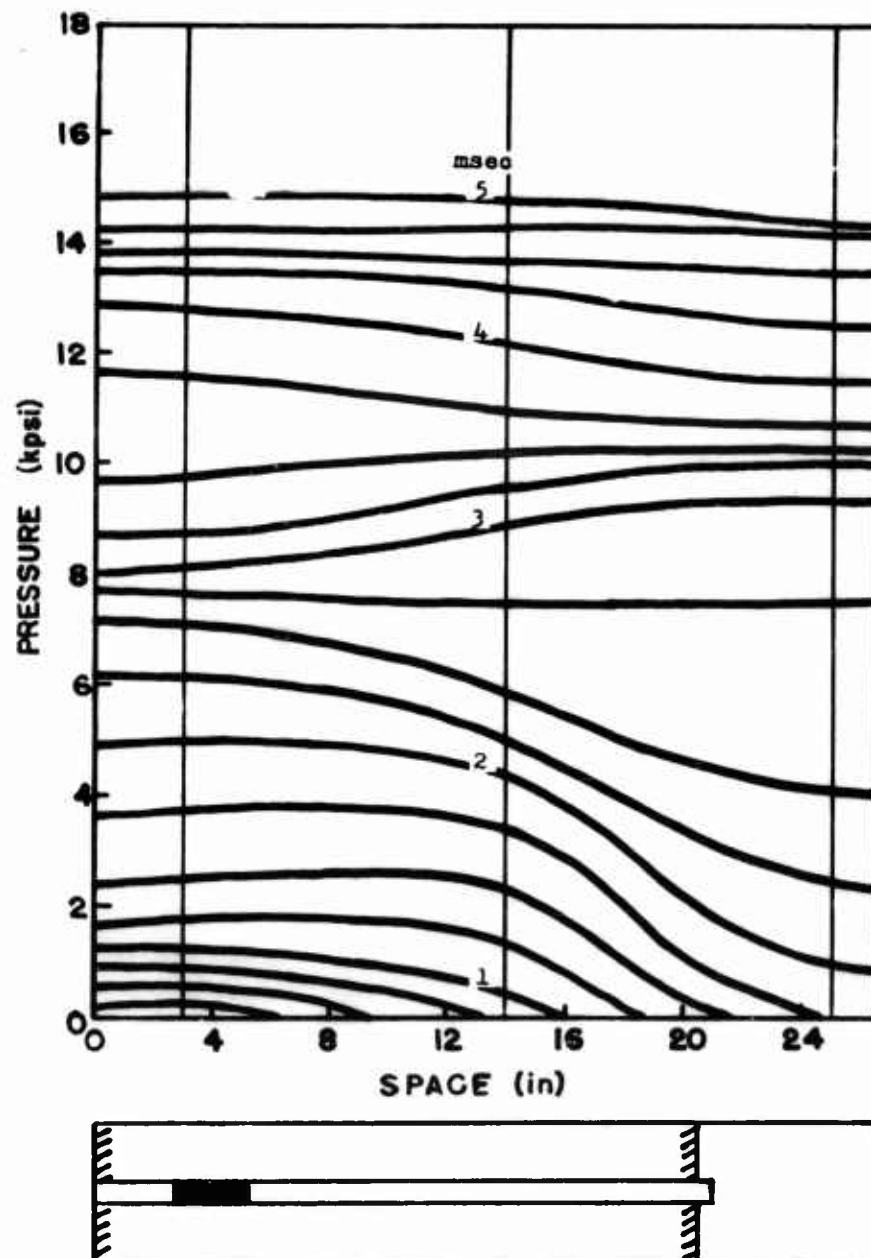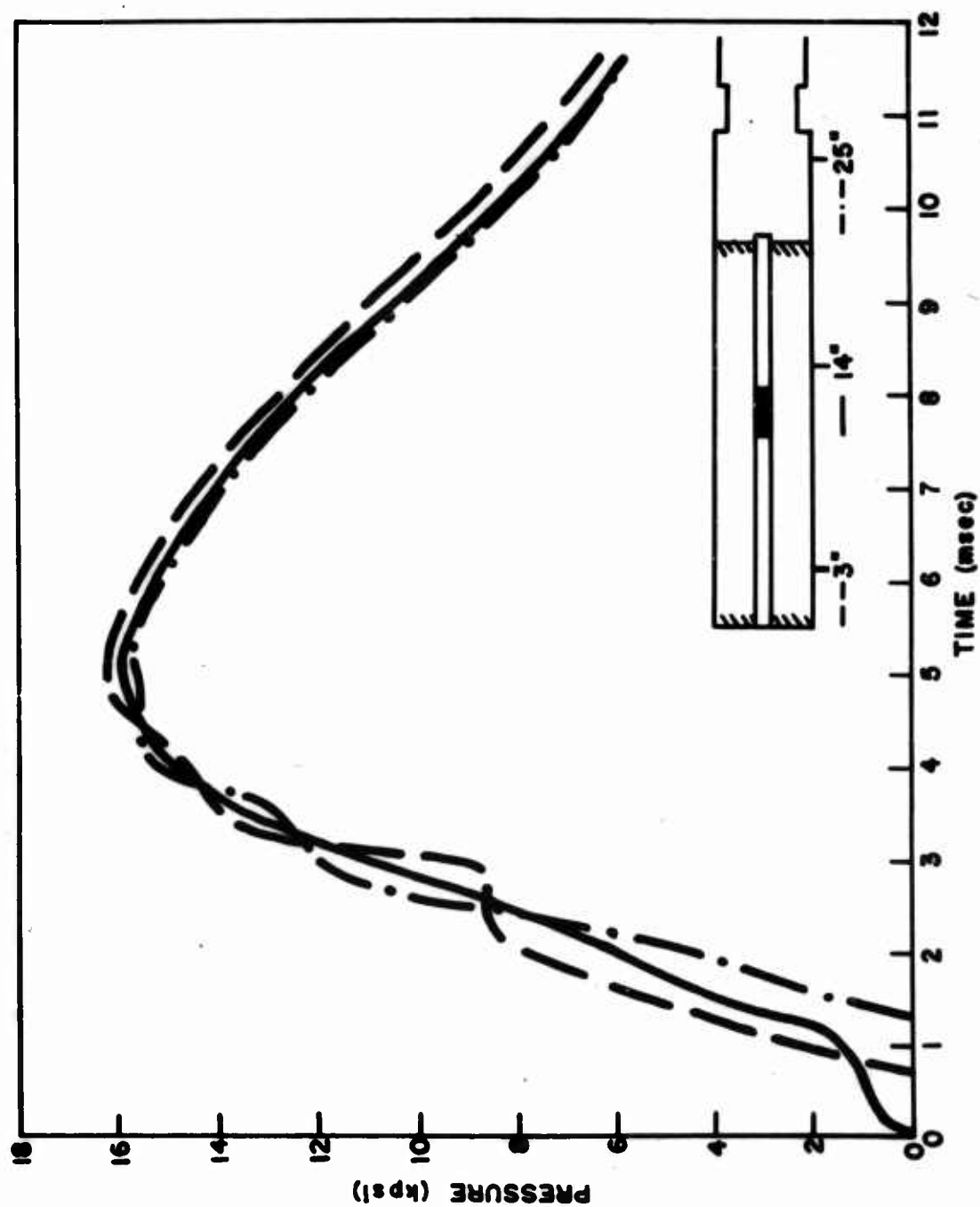FIGURE 15. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN
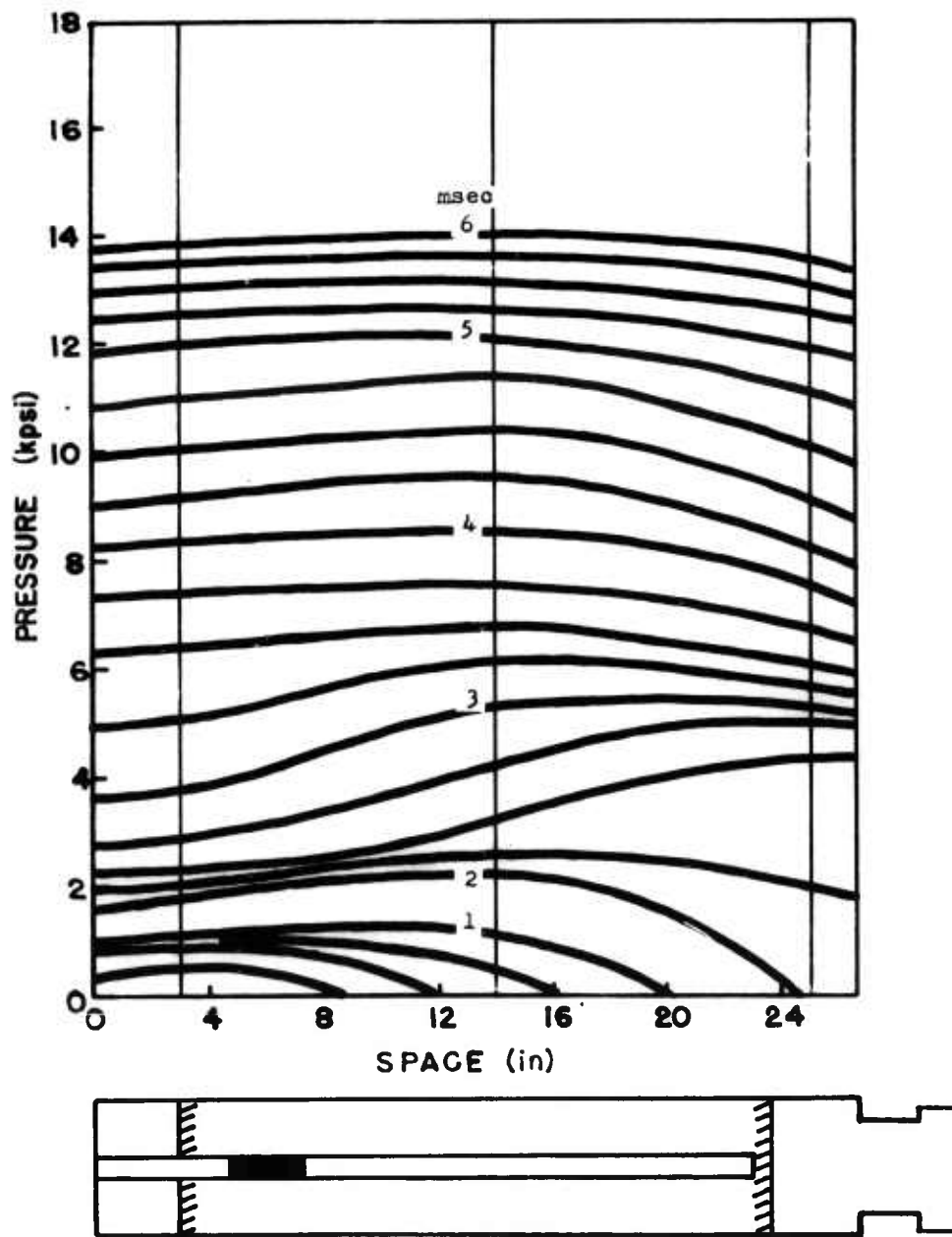
FIGURE 15A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN
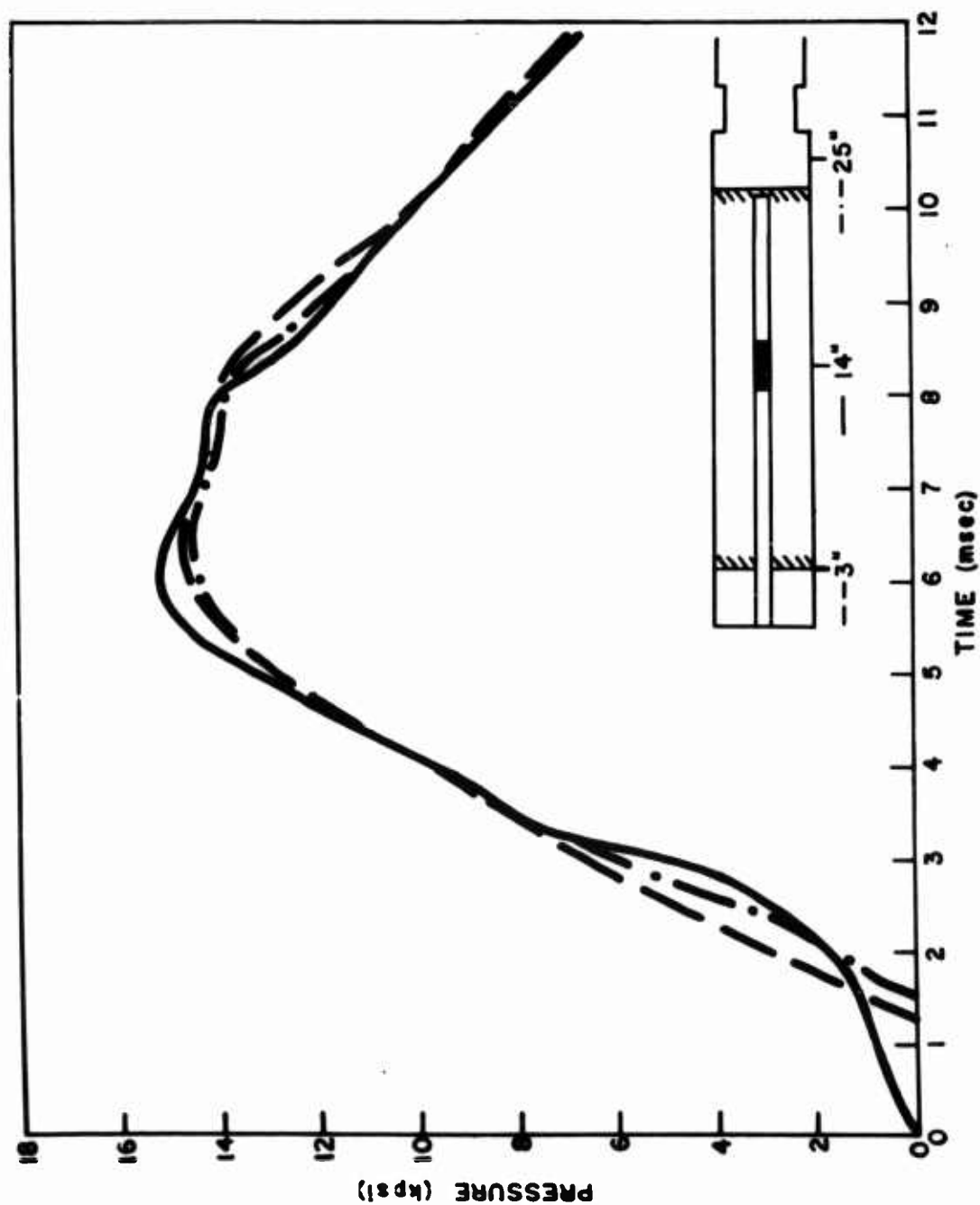
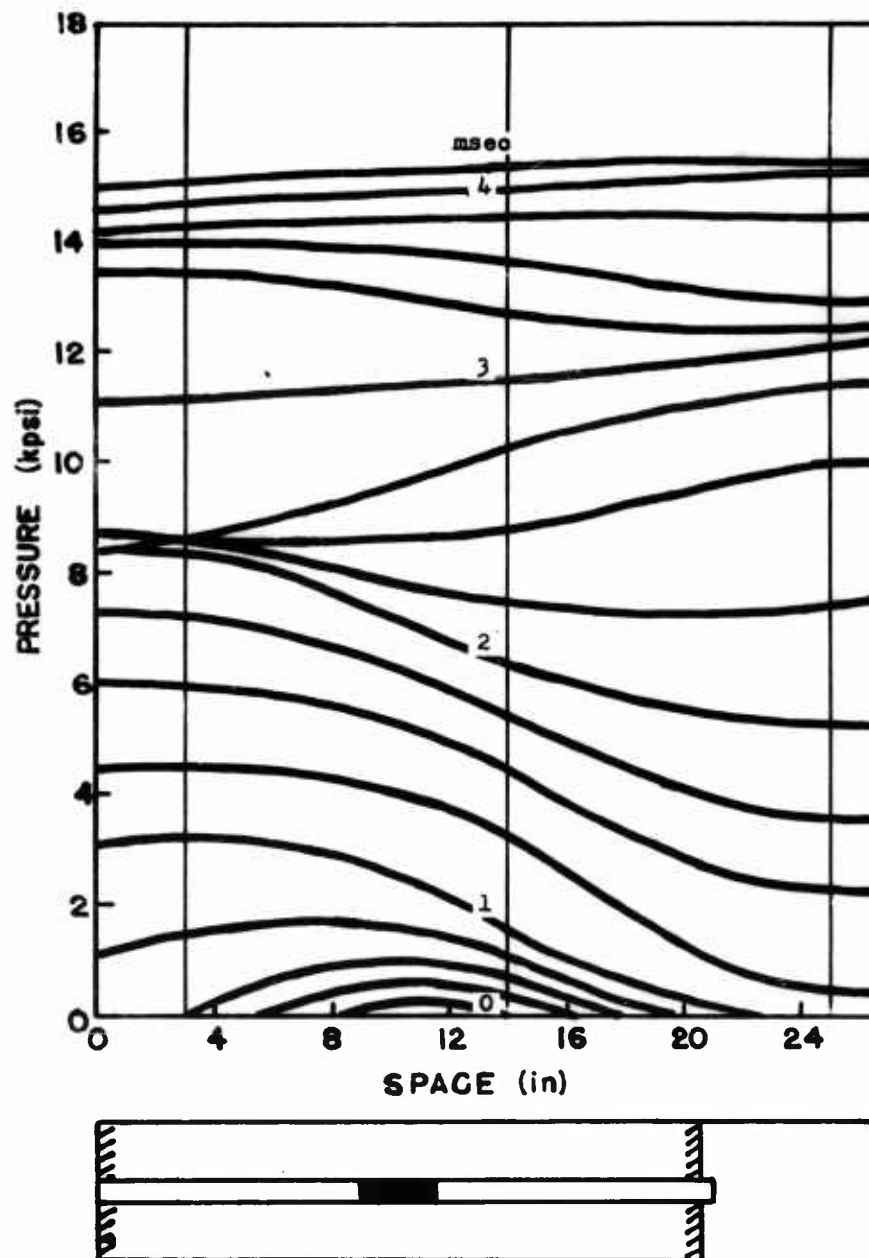FIGURE 16.   PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN
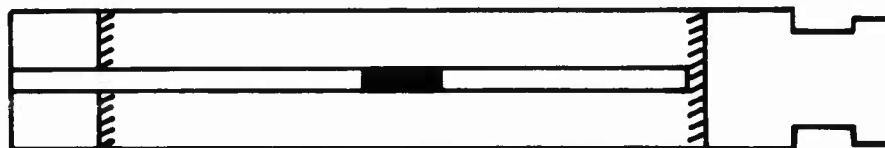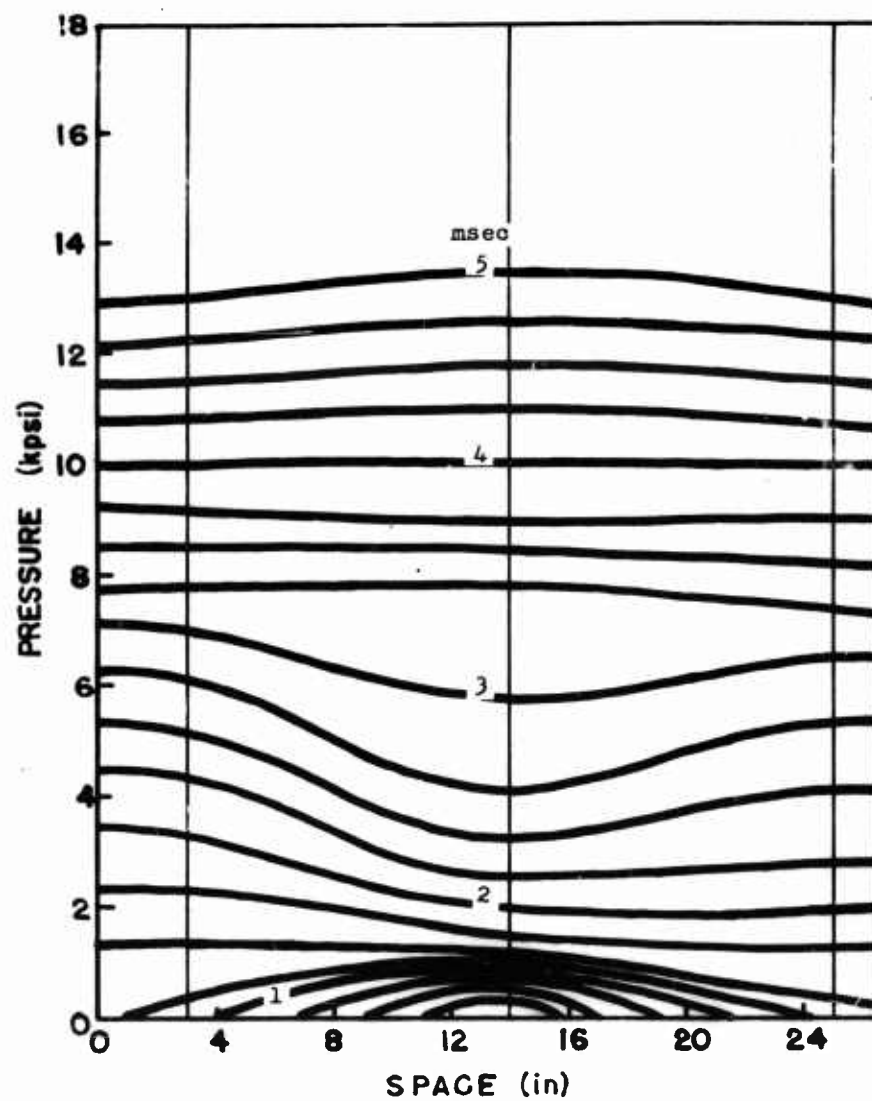
FIGURE 16A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN
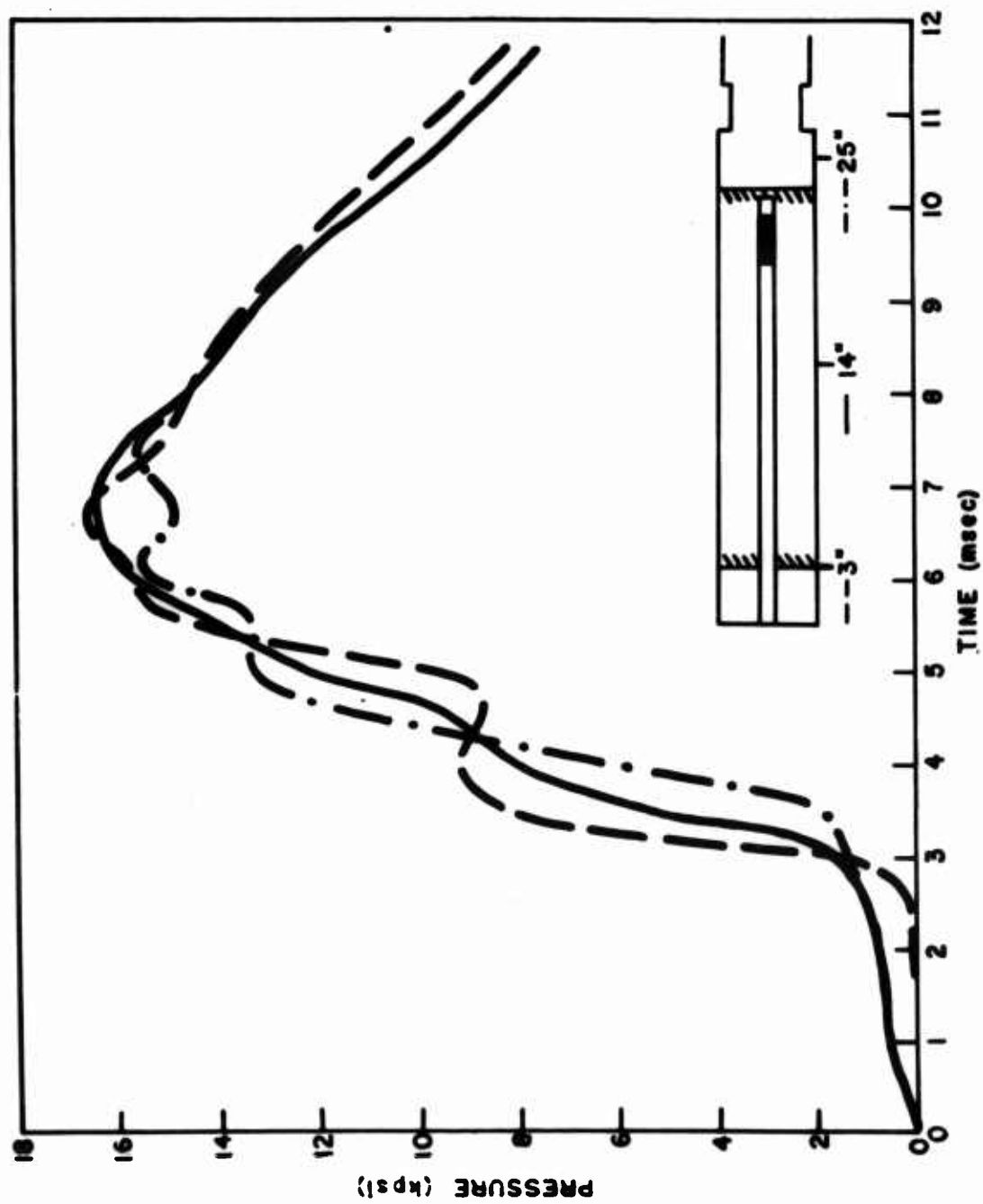
FIGURE 17. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN
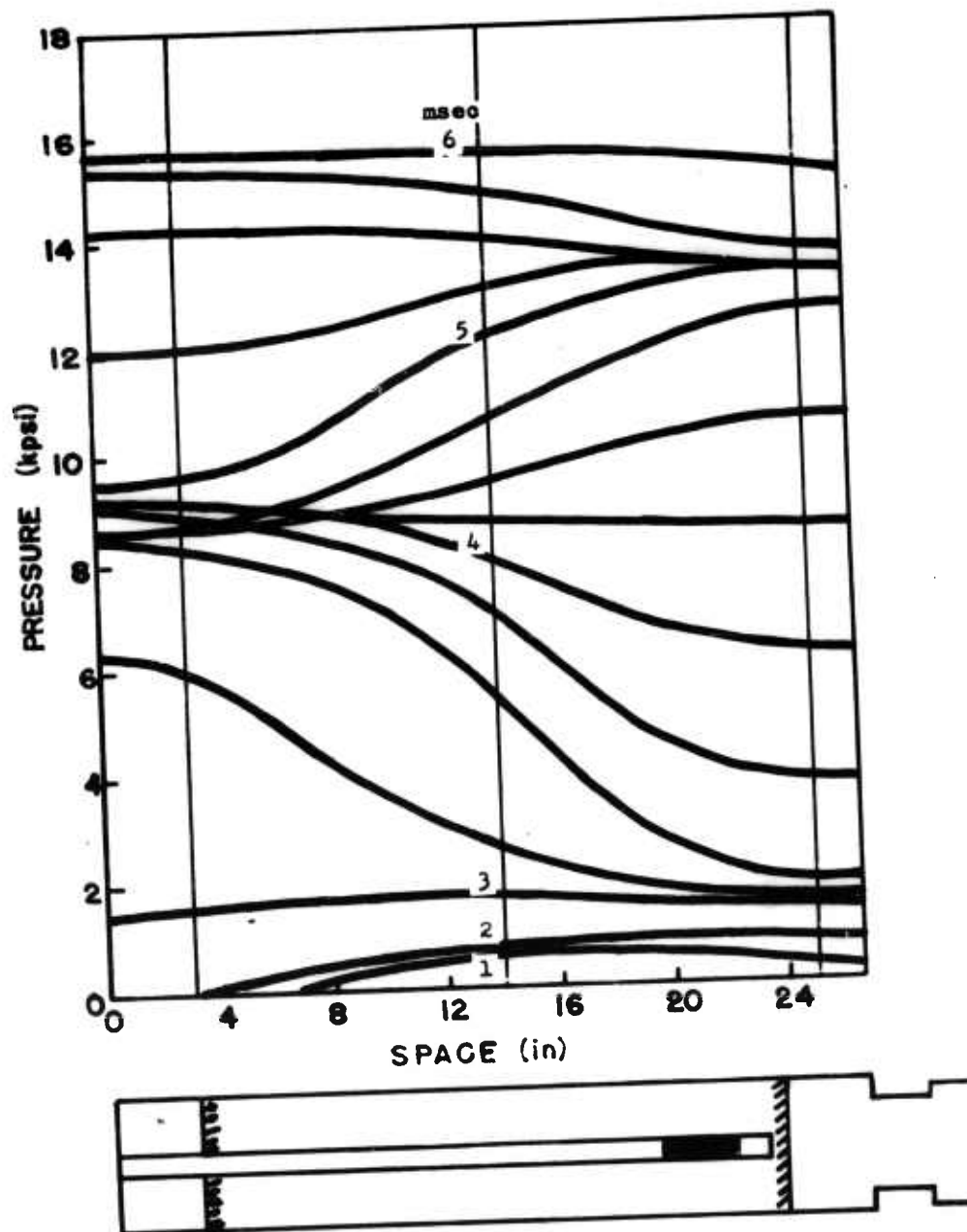
FIGURE 17A

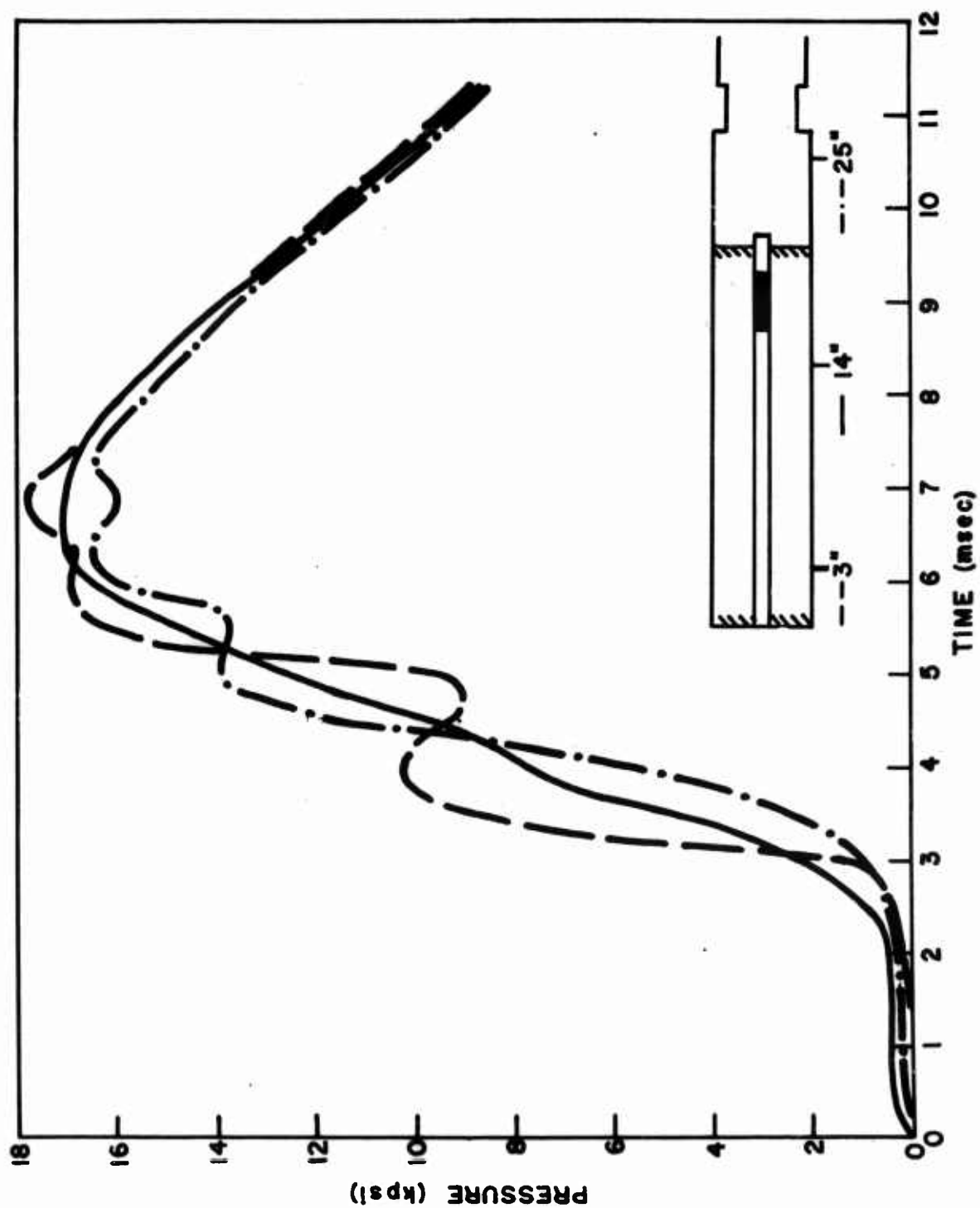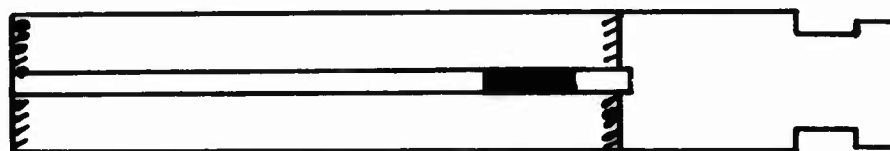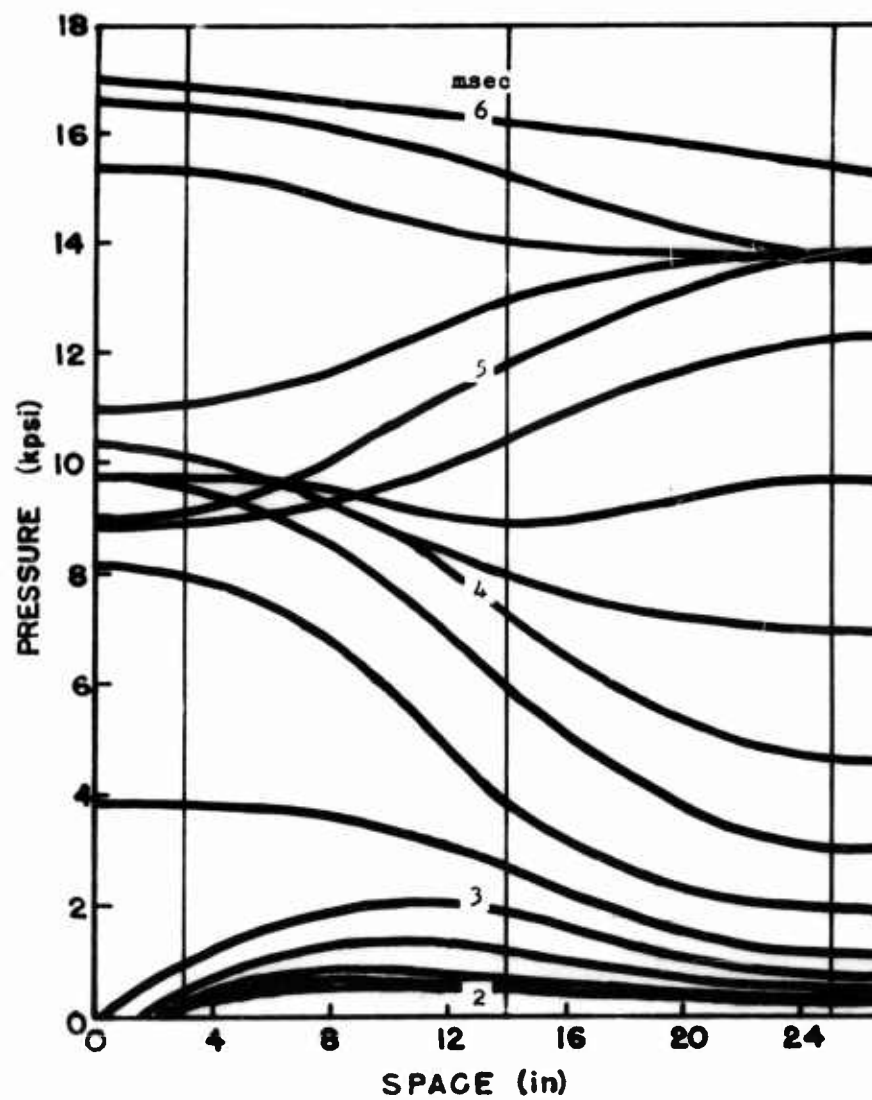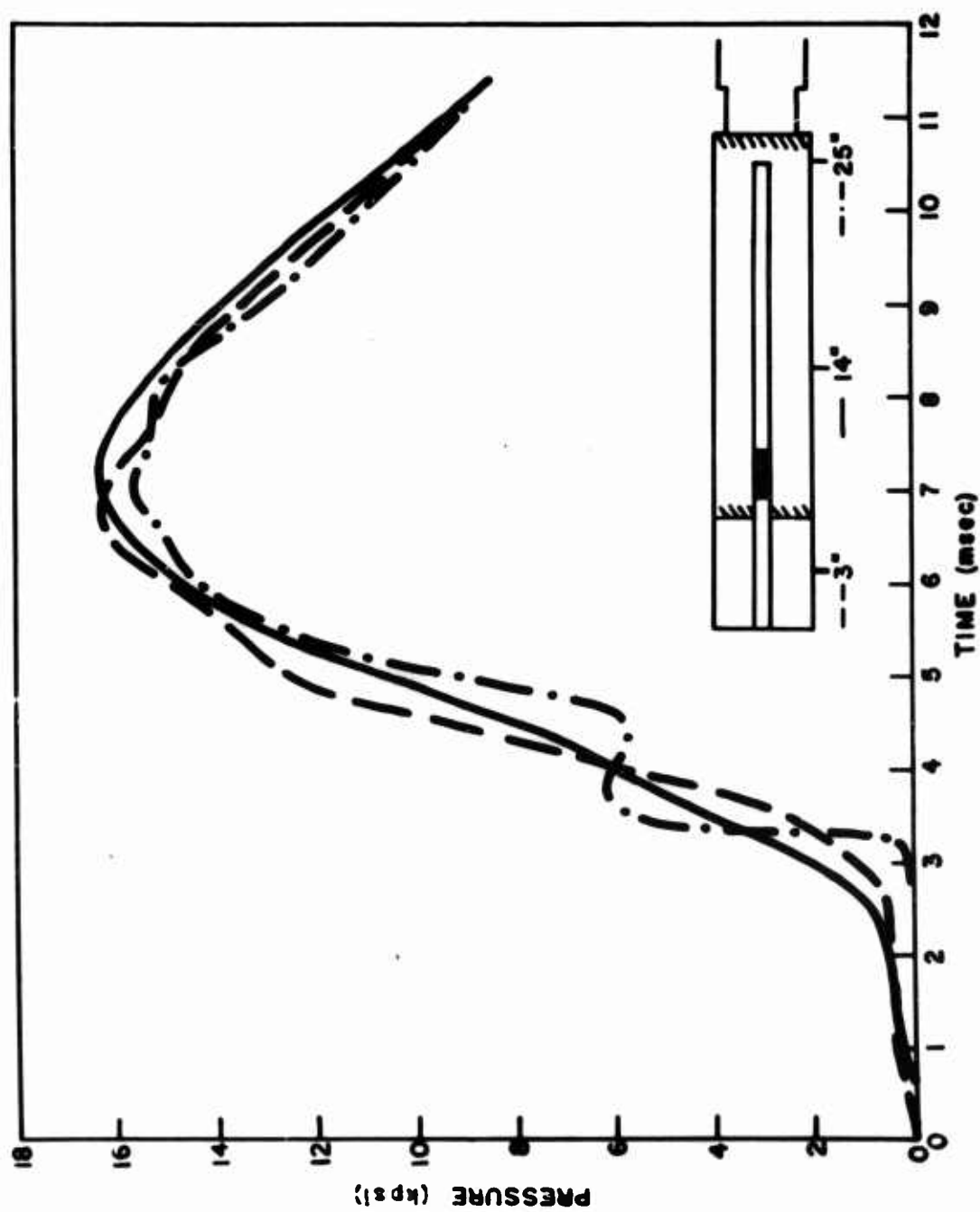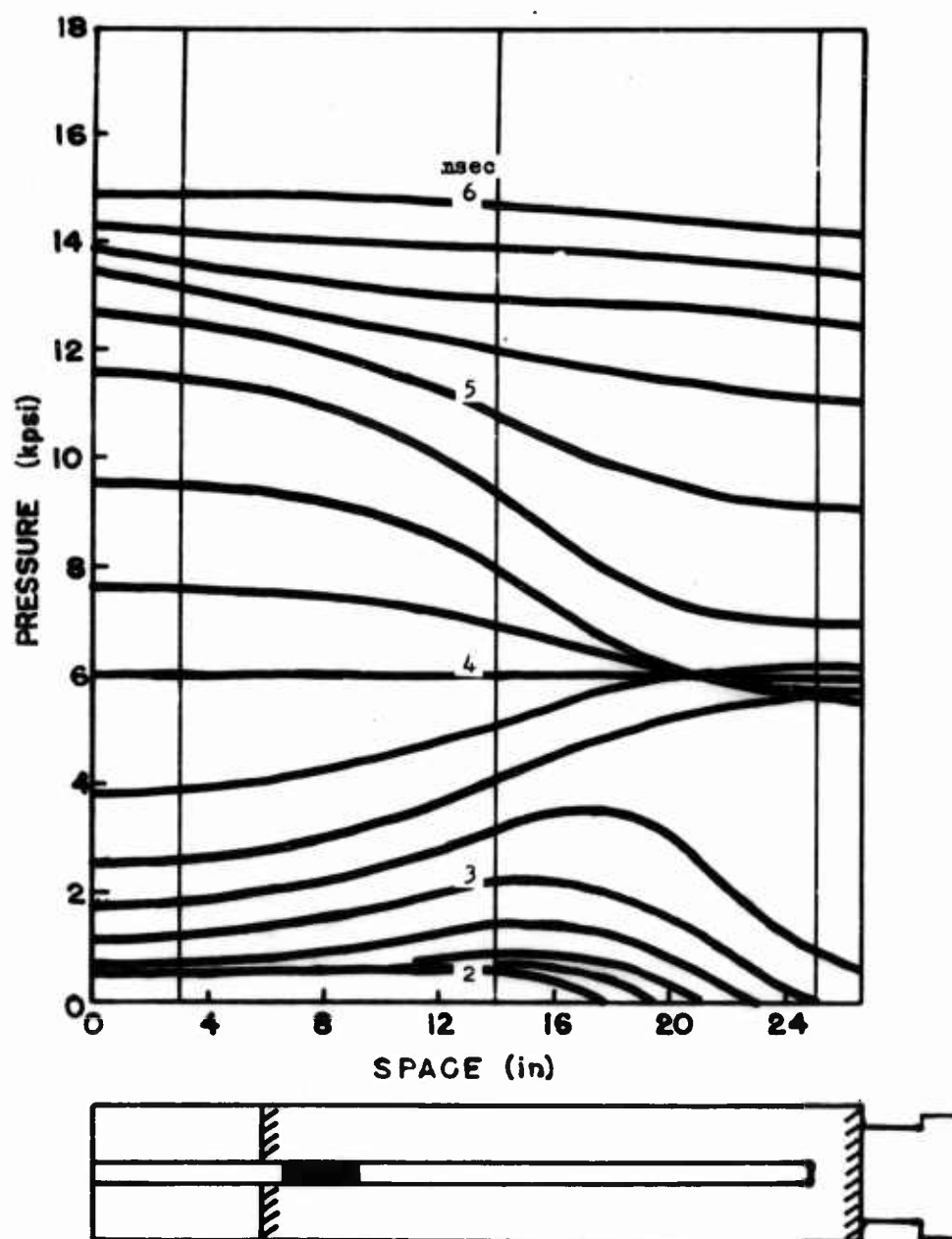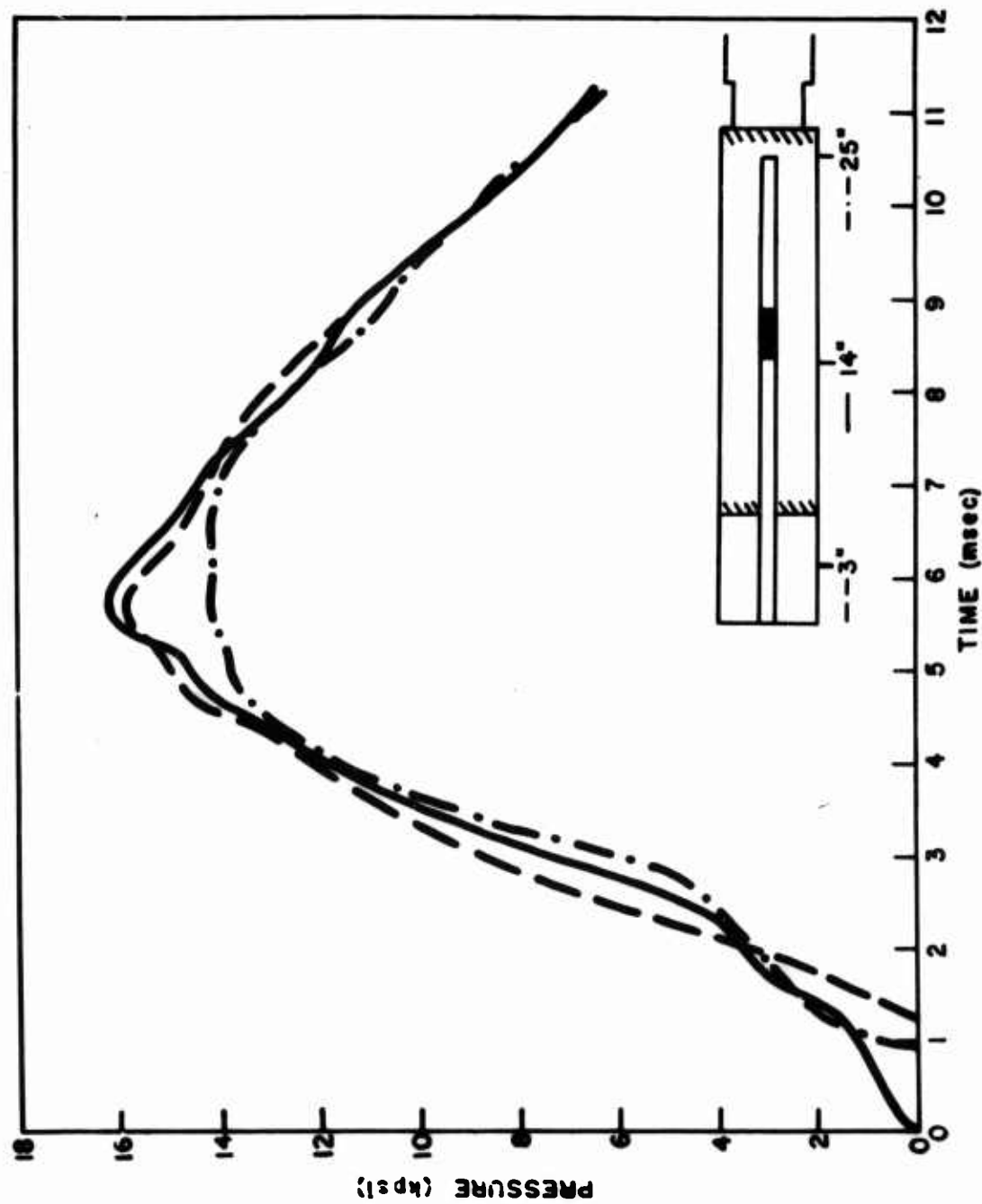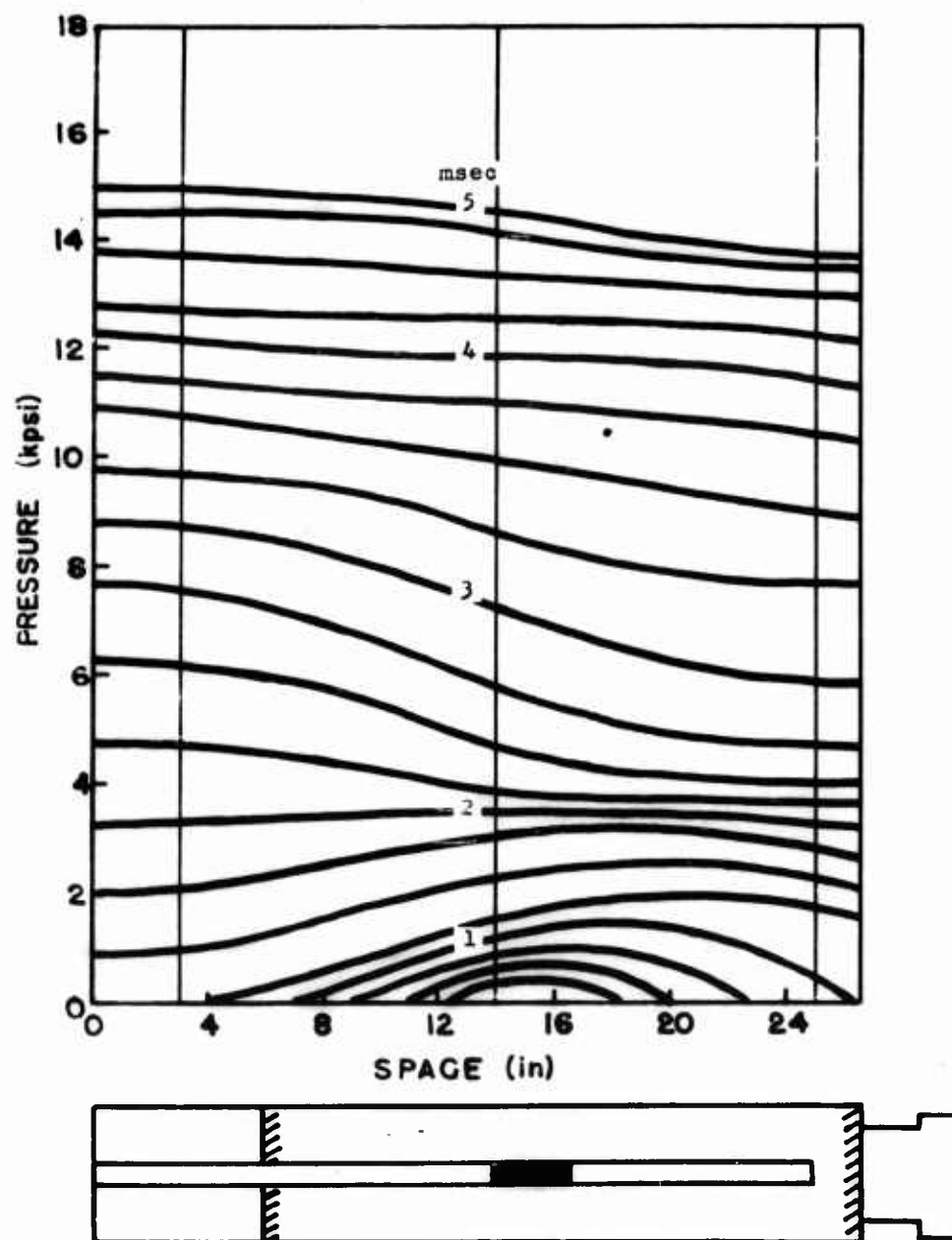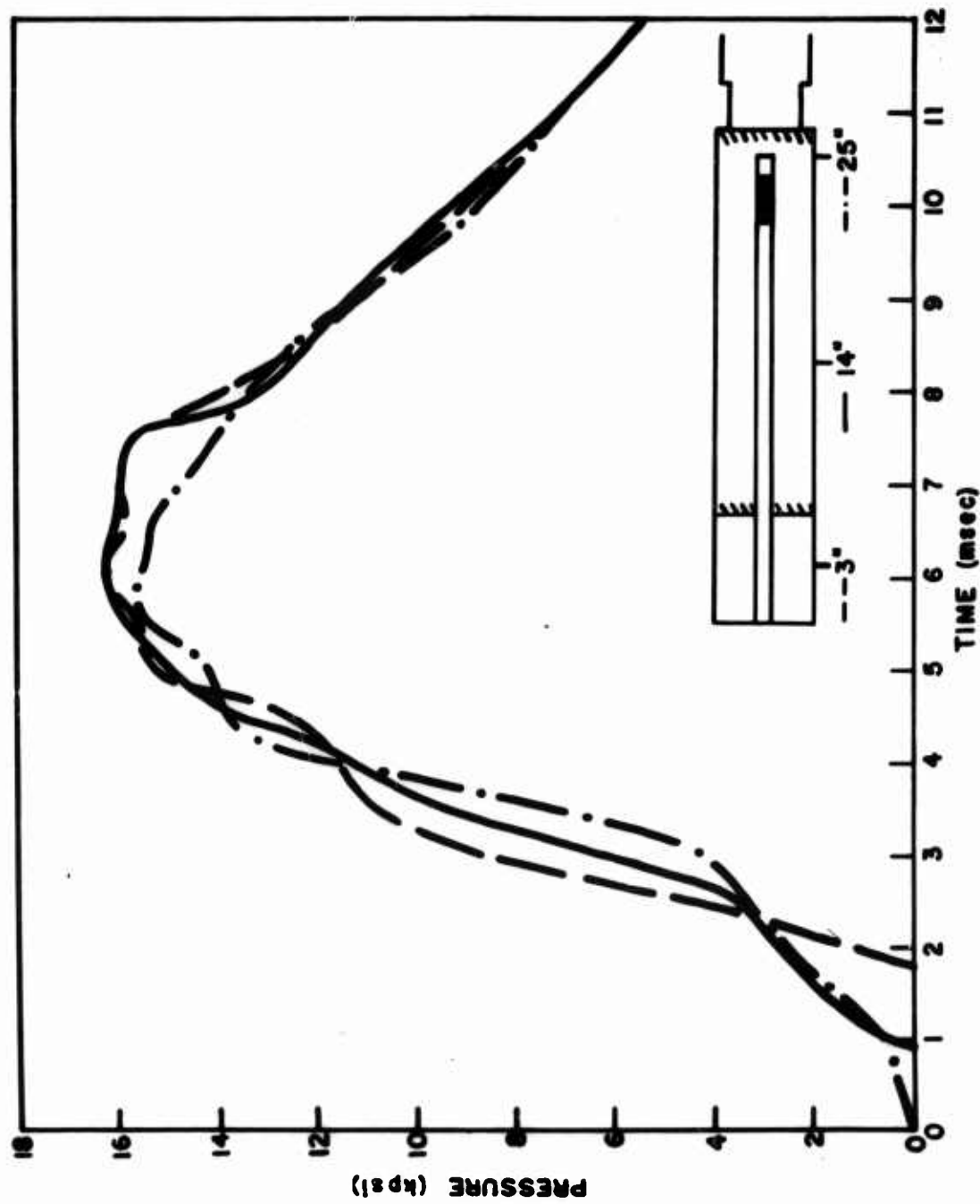PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

plotting the pressures at the three gauge stations at one-
quarter millisecond intervals on pressure-space coordinates
and drawing approximations to cosine curves through the iso-
chronic pressure points. The cosine pressure-space rela-
tions follow from the standing wave character of the pres-
sure waves and were confirmed also by pressure recordings
at stations intermediate between the center and end gauge
stations. These sets of curves are believed to be suf-
ficiently close approximations to the pressure gradients
actually existing in the gun chamber to provide an overall
picture of the pressure-space variations in the chamber and
to be useful in demonstrating the manner in which pressure
gradients in the chamber develop into standing waves.

In the particular charge-igniter-ullage combinations of
these rounds, the point of ignition appeared to dominate
somewhat the location of the ullage in determining both the
phasing and amplitude of the waves formed. The ullages
located at the rear of the chamber appeared somewhat less
effective in forming waves than did the forward ullages.
This is probably to be explained as a result of two factors.
The forward ullages were maintained simply by gluing a
pyralin wad to the case wall immediately ahead of the charge,
while the rear ullages were formed by inserting conventional
cardboard spacers and wads in the base of the case before
pouring the charge. This latter arrangement no doubt
offered greater resistance to the passage of gases and pro-
pellant grains into the free space and also reduced somewhat
the effective volumes of the ullages. On the other hand,
the orifice adjacent to the forward ullages probably tended
t increase somewhat the apparent effective volumes of these
ullages.

In the first three rounds (Figures 9, 10 and 11) the
powder was poured in the conventional manner with the ullage
forward of the powder. With ignition in the rear section of
the charge (Figure 9) a relatively small amplitude wave
developed. The wave amplitude increased somewhat with
center ignition (Figure 10) and became comparatively large
with ignition at the forward end of the charge (Figure 11).
The arrangement of ignition adjacent to the ullage in the
last case is a condition for large amplitude waves, the
effect of the ignition being reinforced by that of the
ullage. In Figure 9, on the other hand, a low amplitude
wave results from the effect of the ullage tending to

neutralize that of the ignition. Figure 10 is an inter-
mediate condition; in the absence of the ullage smooth
pressure-time relations would be anticipated with center
ignition.

In the next set of three rounds (Figures 12, 13
and 14) the ullage was located at the after end of the
chamber. The juxtaposition of ullage and ignition in
Figure 12 is again a condition for pronounced wave develop-
ment, and this is the result obtained. The wave pattern
from this round is somewhat obscured in the higher pressure
levels by the pressure gradient decreasing toward the for-
ward end of the chamber which developed in this phase of the
pressure cycle. It is to be noted that the phasing of the
wave in this case is the reverse of that obtained in the
preceding round with ignition and ullage at the forward end
of the chamber. Moving the ignition to the center of the
charge in Figure 13 reduces the wave amplitude, while moving
the ignition to the forward end of the chamber (Figure 14)
tends to increase the amplitude somewhat over that obtained
with the center ignited round. These results indicate a
reduced effectiveness of the rear ullages as compared to
those forward of the charge. Were these ullages of com-
parable effectiveness to those forward of the charge, a
somewhat greater amplitude wave could be expected in
Figure 13 and a wave of lower amplitude in Figure 14.

In the last set of three rounds (Figures 15, 16 and 17)
the ullage was divided, half being located at each end of
the chamber. In this set the two ullages can be expected
to neutralize each other and the wave action will be that
primarily due to the point of ignition. With the rear
ignition in Figure 15 the phasing of the wave is the same
as that of Figure 12, but the amplitude is less, as would
be anticipated from the reduced ullage adjacent the igniter.
In Figure 16 we have the condition for minimum wave develop-
ment, center ignition and ullage divided equally at the two
ends of the charge. The center ignition tends to produce
higher initial rates of pressure rise at the two ends of
the chamber, resulting in the momentary lower pressure at
the center of the chamber. But upon reflection these higher
end pressures, because of their symmetrical spacing in the
chamber, raise the pressure at the center and establish a
uniform pressure throughout the chamber. With the forward
ignition in Figure 17 a pronounced wave again develops. Here

again the rear ullage appears to be less effective than the forward ullage plus the adjacent orifice, and the amplitude of the wave is somewhat greater than would be expected from equally effective ullages at the two ends of the chamber.

These experimental results substantiate, in all essential aspects, our preliminary working hypothesis of the interaction of point of ignition and ullage in the formation of pressure waves. The hypothesis thus appears to be a useful rule-of-thumb method of predicting the results to be expected from different spatial arrangements of the igniter and ullage in the charge make-up.

Further analysis of the space-time variations in pressure occurring in the above and related firings leads to the conclusion that pressure waves develop in gun chambers as a result of pressure gradients set up in the chamber in the initial stages of the pressure cycle in combination with motion and differential packing of the propellant resulting from the initial gradients. Hence, any parameter which contributes to an initial pressure gradient in the gun chamber becomes a potential source of pressure waves. However, the effect of one parameter may be neutralized by a second which tends to create a gradient in the opposite direction, and conversely the tendency for a wave to develop may be increased by two or more parameters tending to establish a gradient in one direction in the chamber. Motion and differential packing of the powder appears to be of particular significance in determining the amplitude of the pressure wave which eventually develops.

Let us consider this theory in relation to a specific case - that of a round with both ignition and ullage at the forward end of the chamber. The pressure-time-space curves for such a round are presented in Figures 11 and 11A and ideally will be found to be approximately as diagramed as follows:
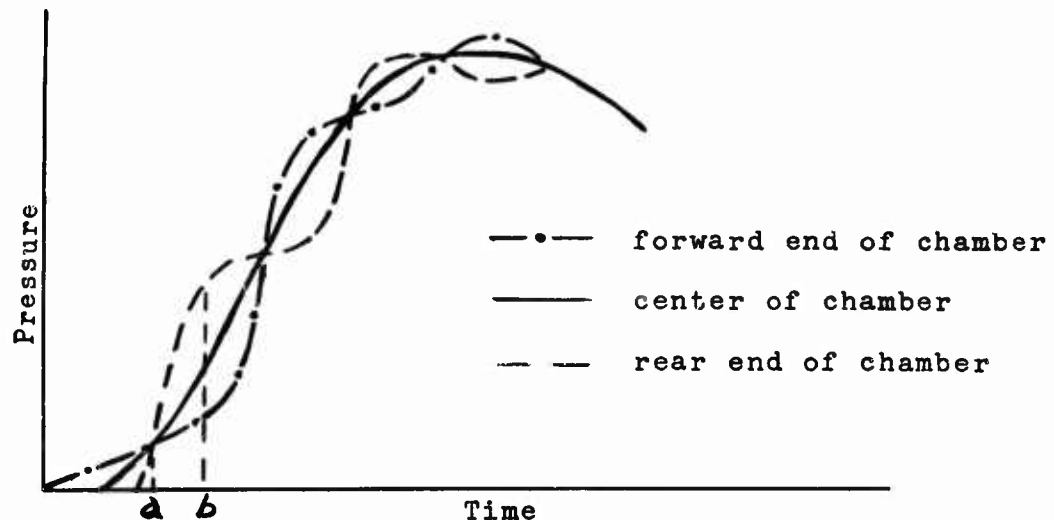
During the time of passage of the ignition front
(considered as the interval between first indications of
pressure at the forward and rear ends of the chamber in
this case) there exists a pressure gradient decreasing
toward the rear of the chamber. It is postulated that
under the influence of this gradient, combined with the
effects from the forward ignition, powder tends to pack
toward the rear of the chamber. The resulting increase in
loading density rearward, coupled with the resistance to
flow of gases offered by the powder bed, results in a rate
of pressure rise at the rear of the chamber greater than
that in the center of the chamber. On the other hand, the
rearward motion of the powder reduces the density of
loading at the forward end of the chamber, tending to
result in a lower rate of burning at this end. The ullage
and orifice contribute to this reduced rate of rise in
pressure by making available additional volume into which
the gases in this section of the chamber can expand.

The differential rate of pressure rise through the
chamber overcomes the initial pressure gradient and in
turn produces a gradient in the opposite direction. This
carries the pressure cycle beyond point a in the above
sketch. The reversed gradient accelerates the powder

grains now toward the forward end of the chamber, and
reduces the amount of powder in the rear of the chamber.
As a consequence, the rate of pressure rise decreases in
this end of the chamber. The gas flow is also toward the
forward end of the chamber during this phase and contri-
butes to the lowered rate of pressure rise. Concurrently,
the grains begin to pack in the forward section of the
chamber. The rate of pressure rise increases at this end
due to the increased burning rate and influx of powder gases
and becomes greater than the decreasing rate at the rear of
the chamber. As the rates of pressure rise at the two ends
become equal (at point b in the sketch) the first quarter
cycle of the pressure wave is completed. The pressure gra-
dient has developed into a standing wave. This quarter
cycle of the wave appears to be critical in that the ampli-
tude of the wave is largely (though not completely) deter-
mined in this interval.

Left to itself, the wave could be expected to continue
in the chamber by reflections at the two ends until damped
out. However, since a large fraction of the charge is yet
unburned at this stage, further concentrations of the grains
are possible under the influence of the pressure gradients
in the wave. These concentrations of grains combined with
the dependence of the burning rate on pressure, are con-
ceived to operate in a regenerative or feed-back manner to
maintain, or even increase, the wave amplitude in later
segments of the wave. In fact, it is a frequent occurrence
for the amplitude of the pressure wave in its second half
cycle to equal or exceed that attained in the first half
cycle.

By this view of wave formation the role of the ullage
is primarily that of augmenting the burning front gradient
set up by the igniter. While its effect in this may be
considerable, the absence of an ullage would not prevent a
gradient being established.

An analysis similar to the above can be carried
through with each of the pressure histories presented in
Figures 9 through 17. Such analyses lead to the conclusion
that the stage is set for the pressure wave to develop by
the initial spacial relations of ignition and ullage and the
redistributions of the charge that take place during the
passage of the ignition front through the powder bed. These

factors appear to determine the variable initial rates of
pressure rise in the different sections of the charge. No
wave would develop if the initial rate of pressure rise was
uniform throughout the chamber. The amplitude of the wave
which develops appears to be a function primarily of the
amount of motion and differential packing of the powder
grains which occur during succeeding phases of the wave.

It has been postulated that pressure waves are stand-
ing waves, their origin and propagation dependent in part
on motion of the powder bed. The question then arises as
to the degree to which these acoustic waves are augmented
by the powder motion. The answer would appear to hinge on
the type of motion which the powder grains experience. If
the powder motion is essentially that of discrete particle
(grain) motion in a fluid stream with each grain moving
essentially independently in response to the forces it
experiences in the pressure wave, then the pressure waves
can be considered to be fundamentally acoustic waves. On
the other hand, if the powder tends to move as a unit mass
in a piston-type motion in response to the pressure dif-
ferentials existing on either side of the mass, then the
pressure variations observed in the chamber would not con-
stitute true acoustic waves, though the pressure changes at
the ends of the chamber might be equivalent to those pro-
duced by an acoustic wave. With this latter type of pro-
pellant motion, the period of oscillation of the pressure
changes would be a function of the oscillating mass (the
total propellant mass) and might be different from the
period of an acoustic wave in the same chamber. In the
experiments considered here, however, the charge masses
have been of an order of magnitude such that, when con-
sidered as unit masses oscillating in a closed tube (the
gun chamber) their natural periods of oscillation are near
that of acoustic waves in the same tube. Thus the question
of the type of propellant motion could not be resolved on
this basis. However, the powder charge is an aggregate of
discrete grains, and considered as such, there would be a
tendency for grains to accumulate at the two ends of the
chamber under the observed pressure gradients rather than
tend to form a compact mass in the center section of the
chamber. While both possible modes of propellant motion
have been considered in this investigation, no experimental
evidence for either mode in favor of the other has been
found. The answer may well lie at some intermediate point

between the two extremes, and becomes a problem for further
investigation if and when successful application of the
proposed theory requires a resolution of the problem.

While the present study has been confined largely to
a study of the contributions of point of ignition and
location and extent of the ullage to the formation of pres-
sure waves, considerable data were reviewed which suggested
that other factors may, under some conditions, contribute
to the formation of waves. These included ignitability and
burning rate of the propellant, temperature of the pro-
pellant, velocity of the ignition front through the pro-
pellant bed, rate of delivery of ignition gases, density of
packing of the charge, and performance of the igniter.
These parameters are listed largely on the basis of cir-
cumstantial evidence - the presence or absence of waves or
the variations in wave amplitudes were observed to accompany
variations in the enumerated parameters on a number of test
firings. However, it does not appear as unreasonable that
variations in most of these parameters could affect wave
formation. For example, the greater the velocity of the
ignition front through the powder bed, the less time there
would be for differences in pressure to develop in different
sections of the charge and hence the amplitude of developing
pressure wave might be reduced. On the other hand,
increased sensitivity of burning rate to pressure would tend
to amplify differences in pressure in different sections of
the charge and thereby increase the pressure gradient in the
chamber. The interdependence of some of these parameters
must also be considered. Thus, the velocity of the ignition
front may depend on rate of delivery of ignition gases and
density of packing of the charge. The performance of the
igniter may depend on its temperature, which is normally the
same as that of the propellant. It is suspected that the
presence or absence of pressure waves at low temperatures
under supposedly identical conditions may be, in many cases,
the result of variations in the performance of the igniter,
such as variation in venting pattern, rather than tempera-
ture effects in the propellant itself. Consideration was
also given to the effect of the rarefaction wave given off
at the base of the projectile on the formation of pressure
waves. Calculations indicate that, while this wave may
contribute to a pressure gradient in the chamber, its
amplitude will be low compared to pressure waves often
developed and can not be considered the sole generator of
pressure waves.

A concomitant result of this study has been the conclusion that pressure waves are not primary sources of velocity variation in guns. Pressure curves with waves appear to be as reproducible generally as "smooth" pressure curves, and the velocity variance within reproducible groups of pressure curves with waves is of the same order of magnitude as that within reproducible groups of "smooth" curves. The idea that pressure waves increase velocity variation seems to have originated in the practice of classifying pressure curves as either "smooth" or "rough" and including in the "rough" group all curves exhibiting pressure waves irrespective of the amplitude of the waves. This practice results in comparing the velocity variation in a homogeneous group with that in a nonhomogeneous group, and greater variation in the latter group is to be expected. If pressure curves are classified in groups on the basis of the amplitudes of the pressure waves, velocity variation can be expected to be reasonably uniform from group to group. This is not to say, however, that the mean velocities of the several groups will necessarily be comparable. Mean rates of pressure rise and mean maximum pressures tend to increase with increasing wave amplitude and these are usually accompanied by higher velocities.

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(b) Seventh AXP Tripartite Conference, Interior Ballistics, (Confidential) April 1956
(c) Bulletin of Second Symposium on Solid Propellant Ignition, Vol I, (Confidential) October 1956
(d) BUORD ltr NP9-Reb-1:LHT:mmt of 14 Jul 1952

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set up in the chamber in the initial stages
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motion and differential packing of the
propellant produced by the gradients.

1. Shock waves
2. Gun barrels
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GUN CHAMBERS, by S. E. Hedden and G. A. Nance.
25 Apr 1957. 18 p. 17 figs.

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set up in the chamber in the initial stages
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motion and differential packing of the
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1. Shock waves
2. Gun barrels
I. Hedden, S. E.

Task: NPG-S6-2d-2-1-56
and
Foundational
Research
Project
NPG-W-1802-4

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